Research Article

Effective Utilization of Synthesized FeS$_2$ for Improving Output Performance of Polycrystalline Silicon Solar Cell

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Solar cells are capable of converting light energy into electrical energy and can completely replace the utilization of fossil fuel energy resources. The current research work majorly concentrates on the development and coating of antireflection materials over the front contact of silicon solar cells. Ferrous disulphide was one of the wide band gap semiconductors employed as a catalytic electrode (in DSSCs), counter electrode (in QDSSCs), and solar energy harvester. FeS$_2$ was synthesized through the hydrothermal method. The antireflective coating was performed over solar cells through the electrospraying technique. It was found that the antireflective material was distributed evenly over the coating substrate at 2 ml/h for 30 (F1), 60 (F2), 90 (F3), and 120 (F4) min. The coated solar cells were examined under neodymium light illumination mimicking sunlight. The effect of electrosprayed FeS$_2$ films adhered over the front contact of solar cells was evaluated using various characterization techniques. The maximum efficiency attained by coated solar cells under indirect light was 19.6%. With the aid of electrospraying, hydrothermally synthesized FeS$_2$ assists incoming photons with energy greater than the bandgap of a procured Si solar cell to take part in the photogeneration process. The maximum Isc and Voc of 38.08 mA/cm$^2$ and 0.655 V were achieved for the F3 solar cell under neodymium irradiation.

1. Introduction

In the present situation, the global population and energy consumption are increasing rapidly. This leads to excessive consumption of limited fossil fuel resources, which delivers toxic gases and pollutes the global atmosphere. Researchers were on the verge of identifying and adopting an alternate energy resource with long-term sustainability, the absence of toxic gas emissions during photocurrent generation, and eco-friendly energy generation [1–3]. Solar energy was one of the promising candidates because it is copious, consistent, and delivers sustainable energy to the present and future world. It can be effectively converted and utilized as heat and electrical energy. With the adaption of solar photovoltaic technology, global electrical energy needs can be easily achieved and do not impose a greenhouse effect on the global atmosphere as compared to conventional energy sources. According to the NREL efficiency chart, a polycrystalline silicon solar cell delivers a higher power output of 23.2%. In India, polycrystalline Si solar cells were preferred mostly for
both industrial and domestic purposes because of their low cost, higher power conversion efficiency, and longer working life [4].

Even though polycrystalline Si solar cells deliver higher power output, some of the notable performance inhibitors were reflection loss, thermal loss, recombination loss, and resistive loss. Among the mentioned losses, reflection loss hinders the electron-hole generation process to a greater extent. Antireflective surface coatings over front contact surfaces have the ability to increase short-circuit current along with a sequential decrease in reflectivity of incident light [5]. Antireflective materials should be transparent, have wide bandgap semiconductors, and have a low cost [6–8]. The optimal refractive index of the anti-reflective material was essential to trap the reflected photons. Materials with similar anti-reflective properties utilized for improving light transmittance were MoSe$_2$, ZnAl$_2$O$_4$, MnFe$_2$O$_4$, CaTiO$_3$, MoS$_2$, SiO$_2$, TiO$_2$, SiO$_2$/TiO$_2$, ZnAl$_2$S$_4$, MoS$_2$, Ta$_2$O$_5$, etc. [9–12]. The transmittance of incident light increases with multilayered coatings, until it achieves optimal thickness. Further coating of material leads to incremental scattering of incident light. The major reason for the drop in cell performance was the cluster formation of coating material [2, 9].

Transition metal sulfides hold a wider energy band gap and better electrical and optical properties. They are semiconducting materials that possess explicit stability and find application in the photovoltaic sector, such as lithium-ion batteries, photo sensible capacitors, and photodetectors [13]. As a performance promoter, fewer sulphur-based materials are involved in the collection of reflected photons such as, Al$_2$S$_3$, MoS$_2$, and ZnS [14–16]. Some of the coating techniques for achieving thin surface films were screen printing, dip coating, sputter deposition, doctor blading, spin coating, laser beam epitaxy, spray pyrolysis, and spray coating [17]. The electrospaying method with optimal running conditions was taken into account for coating the synthesized FeS$_2$ particles [18, 19]. Due to the abundant nature of FeS$_2$, it is utilized as an effective photoabsorber material in place of silicon. The energy band gap of FeS$_2$ was equivalent to 0.95 eV, which was quite nearer to the Shockley-Queisser limit for photoenergy conversion. It also holds higher carrier diffusion lengths and an elevated coefficient of absorption owing to the thickness of the films. This material was also available at a low cost [20]. FeS$_2$ was extensively resistant to a corrosive environment, and hence was used as an alternative for the Pt counterelectrode in DSSCs [21, 22].

This research work majorly concentrates on the development and coating of ferrous disulphide thin films as a perfect light harvesting material for minimizing the light reflection at front contact of crystalline silicon solar cell. However, the synthesized material was confirmed through the X-ray diffraction method and compared with standard JCPDS files. Initially, an adequate quantity of synthesized FeS$_2$ was dispersed with ethanol. Then, the dispersed liquid was electrospayed over the front contact surface of the solar cell. The cross-sectional thickness and material distribution were identified using the FESEM analysis. The coated samples were evaluated using electrical, structural, optical, and thermal studies. The photocurrent generation was measured using a Keithley IV source meter.

2. Materials Used

High-performance polycrystalline silicon solar cells were purchased from Pearlescent Green, Noida. The dimensions of the procured solar cell considered for the performance analysis were 70 mm × 70 mm. Powdered polyvinylpyrrolidone was purchased from Sigma Aldrich and with thiocarbamide and FeSO$_4$. 7H$_2$O was obtained from Lakshita Chemicals, Mumbai. Thiourea, C$_2$H$_5$OH, and sodium hydroxide were brought from Mahadev Chemicals in Chennai. The pure form of sulphur was purchased from Labogens, India.

2.1. Preferred Methodology. The layer-by-layer assembly of ethanol-dispersed FeS$_2$ over the front contact surface of solar cells was performed using the electrospay technique. Initially, the surface of solar cells sensible to solar light was precleaned using ethanol. At preset parameters, the coating of synthesized FeS$_2$ was performed. After each coating, the photovoltaic cell was heat treated at 70°C using a hot air oven. This process was repeated in cyclic manner for attaining a multilayer antireflective coating.

2.2. Synthesis of Metal sulphide-FeS$_2$. One of the abundant transition metal sulfides with explicit optical and electrical properties was FeS$_2$, and it was synthesized using the hydrothermal technique (as indicated in Figure 1). Initiator materials such as iron sulphate heptahydrate and polyvinylpyrrolidone were taken in adequate quantity and then mixed with 0.02 L of distilled water. The mixture was heat treated at 95°C for 0.5 h. Following this, 0.01 mol of thiourea was poured into the mixture and heated at 100°C for 0.5 h. The final mixture was taken into an autoclave. Further, the addition of 0.02 mol of sulphur (in powder form) into the mixture was performed. The autoclave was subjected to a constant heating process for 1 day at 210°C, then allowed to cool at room temperature. Now, 0.01 L of sodium hydroxide solution was added to the final solution. The end product was obtained as a result of centrifugation together with multiple washings of ethyl alcohol and CS$_2$. The resultant powder was dried in an oven at 70°C. The obtained FeS$_2$ powder was dispersed with ethanol and then loaded into the 5 ml surgical syringe. The loaded syringe was placed in the spinneret holder. The surface of the solar cell was wiped thoroughly using ethanol and then placed over the flat plate collector. A high supply voltage of 17 kV was given to the syringe. Under the influence of high electrostatic force, the fine droplets of dispersed liquid get ejected from the syringe and deposited over the silicon solar cell surface. The operating parameters for electrospay deposition are specified in Table 1.

The cross-sectional thickness and distribution of coating materials were observed through FESEM analysis (MIRA 3). By matching the standard JCPDS file, the synthesized FeS$_2$
was confirmed through the XRD technique (XpertPro analyzer). The analysis was performed between the diffraction angles of 20 and 80°, along with the step size and scanning rate, which seemed to be 0.5° and 0.02°/min. Through standard software, the roughness of the coated surface was determined using the atomic force microscopy technique (Tosca 400). In this method, the coated solar cells were scanned at a ×10 m² area for evaluating the surface topography over the front contact surface. The photogenerated energy was calculated with the help of a Keithley I-V source meter at each instant for different solar cells under a neodymium lamp. The input AC regulator and solar power meter help us to tune the neodymium radiation equivalent to solar radiation. The transmittance of various glass samples which are coated under the same operating conditions of different solar cells through UV-Vis-NIR spectroscopy (Cary 5000). The variation in surface temperature of different coated solar cell samples was encountered using an IR fluke thermal imager. The solar simulator setup for determining the power conversion efficiency of solar cells is represented in Figure 2.

### 3. Result and Discussion

Solar cells coated with the FeS₂ powder were assessed through FESEM analysis. From the I-V characteristic curve, the F3 sample holds denser and more uniform coatings of materials. The coating thickness and material distribution were clearly identified using the FESEM technique [23–25]. The cross-sectional thickness of F1, F2, F3, and F4 cells was 0.95, 1.46, 1.78, and 2.31 μm, respectively. From the results, the coating thickness goes on increasing with a gradual increment in coating time. Figure 3(a) indicates the cross-sectional thickness of the F3 sample, while Figure 3(b) represents the distribution of coated materials over the solar cell surface.

From Figure 4, the synthesized FeS₂ was confirmed by matching the obtained XRD results with the predefined JCPDS card: 01–1295. The appearance of steep peaks points out the crystalline nature of FeS₂ powdered material. FeS₂ crystalline material gets oriented predominantly in planes as follows: (1 1 1), (2 0 0), (2 1 0), (2 1 1), (2 2 0), (3 1 1), (2 2 2), (0

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**Table 1: Coating parameters of an electrospray deposition technique.**

| Solar cell | Electrospraying time (min) | Coating thickness (μm) | Plate translational speed (m/s) | Spinneret translational speed (m/s) | Flow rate (ml/h) | Drying temperature (°C) |
|------------|-----------------------------|------------------------|---------------------------------|-------------------------------------|-----------------|------------------------|
| Bare       | 0                           | 0                      |                                 |                                     |                 |                        |
| F1         | 30                          | 0.95                   |                                 |                                     |                 |                        |
| F2         | 60                          | 1.46                   | 0.15                            | 0.1                                 | 2               | 70                     |
| F3         | 90                          | 1.78                   |                                 |                                     |                 |                        |
| F4         | 120                         | 2.31                   |                                 |                                     |                 |                        |
The corresponding diffraction angles were noted as 27.75°, 31.63°, 54.72°, 57.08°, 66.18°, and 74.99°. The crystallite size of synthesized material is found to vary from one particle to another. By means of Debye Scherer equation (1), the average crystallite size of hydrothermally synthesized FeS₂ particles was determined and is tabulated in Table 2. The average crystallite size of FeS₂ particles was about 17.5590 nm. The number of crystallites is added together to form a particle. Hence, the measured particle size is found to be less than the crystallite size of synthesized FeS₂ [26].

Debye Scherer equation,

\[ D = \frac{K \times \lambda}{\beta \cos \theta}, \]

where \( K = \text{Scherer constant (0.9)} \), \( \lambda = 0.15406 \text{ nm} \) (wavelength of incident X-ray source). \( \beta = \text{Line broadening at the} \)

Figure 2: I-V measurement under a simulated light source.

Figure 3: (a) FESEM Cross-sectional image—F3 solar cell sample. (b) FESEM surface morphology—F3 sample.

Figure 4: XRD examination—synthesized FeS₂ powder.
The synthesized powder was examined through HRTEM to obtain the size of the particles [27]. FeS$_2$ powdered particles were added with ethyl alcohol. A small amount of the dispersed mixture was taken with the help of a glass dropper. Then, the glass dropper was pressed against the thin carbon film, which was placed over a copper grid arrangement. An accelerating voltage of 0.2 MV was supplied to the copper grid. The examined particles were of different sizes, varying from 67.43 nm to 310.75 nm. From Figure 5, HRTEM studies of particles appeared to have irregular shapes.

The surface topography at near atomic resolution for coated solar cells was analyzed using the AFM technique [28]. Figure 6 represents the 3D morphology of coated samples evaluated through AFM studies. The RMS values of surface roughness for coated solar cells were found to be 55, 89, 103, and 133 nm, respectively. Various FeS$_2$ electrospayed samples were examined under a fixed scanning area in a tapping mode. The coating material firmly gets adhered to the front contact surface, with slight variations in the magnitude of surface roughness for different solar cells. It was found that an increase in coating time increases the surface roughness and thickness of the coated film. The roughened surface of coated cells facilitates the incoming photons to impregnate into the junction of the p-n region. This should enhance the power conversion efficiency of coated solar cells.

The transmittance of coated samples at varying coating times was analyzed through UV-Vis spectroscopy [17, 29]. The obtained transmittance studies were graphically represented in Figure 7. The coated samples were analyzed with respect to reference glass slides. Among all coated glass slides, the triple-layer electrospayed specimen exhibits maximum transmittance than other samples. The size of the glass sample for optical analysis was 2.54 cm $\times$ 7.62 cm. The maximum transmittances obtained for one, two, three, and four-layered glass slides were 84.6, 86.2, 92.7, and 82.5%, respectively. The refractive index of the sample was found to be varying and was measured at different wavelengths. As the refractive index decreases, light transmittance tends to rise for coated samples. The refractive indexes of FeS$_2$-coated samples were determined as 4.5, 4.1, 3.7, and 3.5 using Eq. (2). Here, $n_2$ and $n_0$ represent the refractive index of thermally evaporated ZnSe and atmospheric air. The antireflective material should be selected by considering its refractive index and transparent nature. For the coated thin films with enhanced light transmittance, hall mobility reaches a maximum of 14.97 cm$^2$ V$^{-1}$ s$^{-1}$ (F3). This indicates the traption of the maximum possible photons reflected from the solar cell surface to achieve the maximum photocurrent generation.

$$n_1 = \sqrt{n_0 \times n_2}. \tag{2}$$

The generated electrons flow into the closed circuit and were measured using an I-V source meter. The source meter was interfaced with the display device. The measured electrical characteristics of coated and uncoated samples were tabulated in Table 3. With the experimental data, the characteristic curve was traced with open-circuit voltage against short-circuit current. The analysis of solar cells was performed under constant light irradiation (neodymium light illumination). From Figure 8, the obtained power conversion efficiencies of uncoated and F3 solar cell samples were found to be 14.88% and 19.6%, respectively. The triple-layer electrospayed FeS$_2$ sample showed almost a 5% increase in power conversion efficiency as compared to an uncoated solar cell. The solar cell performance gradually increases until reaching optimal coating thickness. At optimal coating thickness, it promoted electron mobility reduced photon reflection with the front contact surface and

| 2θ (degrees) | FWHM (radians) | Crystallite size (nm) | Average crystallite size $D$ (nm) |
|-------------|----------------|----------------------|---------------------------------|
| 28.55       | 0.613          | 13.37258833          |                                 |
| 35.47       | 0.692          | 12.05299818          |                                 |
| 39.11       | 0.481          | 17.52714833          |                                 |
| 41.48       | 0.32           | 26.54617406          |                                 |
| 58.05       | 0.42           | 21.63174626          | 17.55903221                     |
| 62.06       | 0.63           | 14.42116417          |                                 |
| 64.24       | 0.534          | 17.36140617          |                                 |
elevated the built-in voltage. After 1.78 μm of thickness, there is a drop in solar cell efficiency due to increased reflectivity at the coated surface for the F4 solar cell as compared to the F3 solar cell. Only a certain quantity of photons were involved in the photogeneration process, which was the major reason for the drop in cell performance. The remaining photons were dissipated as heat energy, which was responsible for increasing solar cell temperature. Thus, increased cell temperature reduces the electrical conductivity of a solar cell [8, 30, 31].

The resistivity of coated and uncoated solar cells was assessed through four-probe methods (as represented in Figure 9). The best-performing solar cell (F3) experiences hall mobility and resistivity at 14.97 cm²V⁻¹ s⁻¹ and 2.35 × 10⁻³ Ωm, respectively. The parameters related to the electrical properties such as hall mobility, carrier concentration, and electrical resistivity were evaluated and tabulated in Table 4. The presence of Fe was responsible for the increment in the overall electrical conductivity of coated solar cells. The spin-coated surface films experience decremented electrical resistivity until reaching the optimal coating thickness of 1.78 μm; beyond that, resistivity starts increasing. This is because clustered coated materials inhibit the penetration of photons into the front contact of the solar cell [12, 17]. The rate at which excitons were generated and recombined was dependent on hall mobility. Hall mobility is the measure of representing the generated electron mobility in photovoltaic cells. Certain noticeable changes occur in the size of the crystal without altering the orientation of the crystal, which was the major reason for incremental electrical resistivity (for the F4 sample).
The thermal imaging technique was one of the nondestructive examination techniques employed in the fields of energy audit, ecology, foundry and manufacturing industries, etc. The coated and uncoated solar cells get heated under continual light irradiation. An increase in surface temperature reduces photoelectron generation [32]. This results in a drop in the power conversion efficiency of solar cells. Until now, temperature studies on coated solar cells were not well explored. The measured solar cell temperatures for uncoated and coated solar cells were 60.7, 55.1, 53.3, 49.9, and 52.1°C, which were clearly evident from Figure 10. In general, the performance of semiconductors decreases with an increase in operating temperature. For solar cells, the operating temperature directly affects the magnitude of Voc.

| S.No | Layer | Isc (mA/cm²) | Voc (V) | FF (%) | Rsh (Ω m) | Rs (Ω m) | Efficiency (%) | Thickness (μm) |
|------|-------|--------------|---------|--------|-----------|-----------|----------------|----------------|
| 1    | F1    | 33.92        | 0.641   | 75.9   | 1478      | 0.51      | 16.50272       | 0.97           |
| 2    | F2    | 35.61        | 0.647   | 76.8   | 1763      | 0.48      | 17.69447       | 1.25           |
| 3    | F3    | 38.08        | 0.655   | 78.6   | 1952      | 0.45      | 19.60473       | 1.78           |
| 4    | F4    | 36.47        | 0.648   | 77.7   | 1884      | 0.42      | 18.3625        | 2.19           |
| 5    | Uncoated | 31.82        | 0.632   | 74     | 1275      | 0.53      | 14.88158       | 0             |

**Table 3: I-V assessment under a neodymium light source.**

**Figure 8:** The outcome of photogeneration of various coated FeS₂ electrospayed solar cells under neodymium light.

**Figure 9:** Electrical resistivity of coated samples.
and $I_{SC}$. Increasing cell temperature slightly increases the short circuit current but decreases the open circuit voltage. This phenomenon results in shifting the $I$-$V$ curve toward the origin, leading to a decrease in the measured fill factor. Due to the decreased energy band gap, minimal energy was required for the electron to jump from the valence to the conduction band. This facilitates the mobility of generated electron and hole pairs. Hence, $I_{SC}$ increases in a very minimal quantity with reference to temperature [33].

In most cases, the photogeneration ability decreases with an increase in cell temperatures, owing to enhanced electrical resistivity. Due to a higher number of excitons generation and recombination, maximum hall mobility was achieved for the F3 sample. The charge carrier mobility decreases with an increase in photon reflection at the solar cell surface, leading to an increase in the solar cell temperature. From the observed results, photon scattering at the solar cell surface promotes heat flux and hinders photocurrent generation.

### 4. Conclusion

With the aid of certain precursor materials such as polyvinylpyrrolidone, thiocarbamide, iron sulphate heptahydrate, and NaOH, FeS$_2$ was synthesized through the hydrothermal method. From the results of XRD, the miller

| S.No | Layer | Resistivity ($\Omega \cdot m$) | Closed temperature (°C) | Hall mobility (cm$^2$·V$^{-1}$·s$^{-1}$) |
|------|-------|-----------------------------|-------------------------|---------------------------------------|
| 1    | F1    | $4.95 \times 10^{-3}$       | 55.8                    | 11.43                                 |
| 2    | F2    | $3.89 \times 10^{-3}$       | 53.2                    | 13.16                                 |
| 3    | F3    | $2.35 \times 10^{-3}$       | 49.7                    | 14.97                                 |
| 4    | F4    | $3.19 \times 10^{-3}$       | 52.3                    | 13.09                                 |
| 5    | Uncoated | $6.71 \times 10^{-3}$   | 59.4                    | 8.76                                  |

**Table 4: Electrical resistivity and hall mobility of various coated samples.**

**Figure 10: IR thermal imaging under a simulated light source (a) uncoated, (b) F1, (c) F2, (d) F3, and (e) F4.**
indices approximately coincide with the standard JCPDS file. Also, the average crystallite size of hydrothermally synthesized samples was determined to be approximately 17.5590 nm. From FESEM, the coating thickness for the best operating solar cell (F3) was 0.97, 1.25, 1.78, and 2.19 μm. Various layers of FeS₂ over silicon substrates were confirmed through a continual increase in coating thickness. The maximum number of photons get diffused in the F3 sample, with a corresponding transmittance of 92.7%. A pyrite-structured antireflective material with three coating layers experiences a maximum power conversion efficiency of 19.6%. Through IV studies, the F3 solar cell exhibits a higher Voc, which increases from 14.88% (bare cell) to 19.6%. With a further increase in coating thickness, Isc tends to drop, resulting in minimal output photocurrent generation. From the observed results, solar cell performance decreases (for the F4 solar cell) with increases in surface temperature and electrical resistivity. As a result, synthesized FeS₂ was found to be transparent, antireflective, and minimize photon scattering at the solar cell surface.

Data Availability

No data were used to support the study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] G. Velu Kaliyannan, S. V. Palanisamy, M. Palanisamy et al., “Utilization of 2D gahnite nanosheets as highly conductive, transparent and light trapping front contact for silicon solar cells,” Applied Nanoscience, vol. 9, no. 7, pp. 1427–1437, 2019.
[2] D.-W. Kang, J.-Y. Kwon, J. Shim, H.-M. Lee, and M.-K. Han, “Al₂O₃ antireflection layer between glass and transparent conducting oxide for enhanced light trapping in microcrystalline silicon thin film solar cells,” Solar Energy Materials and Solar Cells, vol. 101, pp. 22–25, 2012.
[3] B. Liu, Q. Zhao, and P. Zheng, “Optical properties of amorphous silicon thin films fabricated by RF magnetron sputtering,”Photonics and Optoelectronics Meetings (POEM) 2008: Optoelectronic Devices and Integration, vol. 7279, pp. 1–11, 2009.
[4] V. Balaprakash, P. Gowrisankar, S. Sudha, and R. Rajkumar, “Aluminum doped ZnO transparent conducting thin films prepared by sol-gel dip coating technique for solar cells and optoelectronic applications,” Materials Technology, vol. 33, no. 6, pp. 414–420, 2018.
[5] D. Chen, “Anti-reflection (AR) coatings made by sol-gel processes: a review,” Solar Energy Materials and Solar Cells, vol. 68, no. 3–4, pp. 313–336, 2001.
[6] A. M. K. Dagamseh, B. Vet, F. D. Tichelaar, P. Sutta, and M. Zeman, “ZnO:Al films prepared by rf magnetron sputtering applied as back reflectors in thin-film silicon solar cells,” Thin Solid Films, vol. 516, no. 21, pp. 7844–7850, 2008.
[7] J. Yoo, J. Lee, S. Kim et al., “High transmittance and low resistive ZnO: Al films for thin film solar cells,” Thin Solid Films, vol. 480, pp. 213–217, 2005.
[8] H. Hattori, “Anti-reflection surface with particle coating deposited by electrostatic attraction,” Advanced Materials, vol. 13, no. 1, pp. 51–54, 2001.
[9] S.-Y. Lien, D.-S. Wuu, W.-C. Yeh, and J.-C. Liu, “Tri-layer antireflection coatings (SiO₂/SiO₂–TiO₂/TiO₂) for silicon solar cells using a sol–gel technique,” Solar Energy Materials and Solar Cells, vol. 90, no. 16, pp. 2710–2719, 2006.
[10] J. Jung, A. Jannat, M. S. Akhtar, and O. B. Yang, “Sol–Gel deposited double layer TiO₂ and Al₂O₃ anti-reflection coating for silicon solar cell,” Journal of Nanoscience and Nanotechnology, vol. 18, no. 2, pp. 1274–1278, 2018.
[11] N. F. Habubi, R. A. Ismail, K. A. Mishjil, and K. I. Hassoun, “Increasing the silicon solar cell efficiency with nanostructured SnO₂ anti-reflecting coating films,” Silicon, vol. 11, no. 1, pp. 543–549, 2019.
[12] Chanta, E. Chhoonmeanee, A. Garchchareon, D. Wongratanaphisan, S. Phadungditidha, and S. Choopun, “Development of anti-reflection coating layer for efficiency enhancement of ZnO dye-sensitized solar cells,” Journal of Nanoscience and Nanotechnology, vol. 15, no. 9, pp. 7136–7140, 2015.
[13] K. W. A. Chee, Z. Tang, H. Lù, and F. Huang, “Anti-reflective structures for photovoltaics: numerical and experimental design,” Energy Reports, vol. 4, pp. 266–273, 2018.
[14] V. Gobinath, R. Rajasekar, C. Moganapriya et al., “Surface engineering of zinc sulphide film for augmenting the performance of polycrystalline silicon solar cells,” Chalcogenide Letters, vol. 18, no. 7, pp. 375–384, 2021.
[15] P. Shankumugam, R. Rathanasamy, G. Velu Kaliyannan, S. Sivaraj, M. Chinnasamy, and M. S. Anbupalani, “Performance enhancement of polycrystalline silicon solar cell through sputter coated molybdenum disulphide surface films,” Materials Science, vol. 28, no. 2, pp. 157–163, 2012.
[16] G. Velu Kaliyannan, S. V. Palanisamy, R. Rathanasamy et al., “An extended approach on power conversion efficiency enhancement through deposition of ZnS-AlS23 blends on silicon solar cells,” Journal of Electronic Materials, vol. 49, no. 10, pp. 5937–5946, 2020.
[17] A. Verma, F. Khan, D. Kumar et al., “Sol–gel derived aluminum doped zinc oxide for application as anti-reflection coating in terrestrial silicon solar cells,” Thin Solid Films, vol. 518, no. 10, pp. 2649–2653, 2010.
[18] S. Santhosh, R. Rajasekar, V. Gobinath, C. Moganapriya, S. Arun Kumar, and A. Manju Sri, “Influence of electro-sprayed MoSe₂ antireflective surface coatings on performance of multicrystalline silicon solar cell,” Solar, vol. 1, pp. 1–13, 2021.
[19] R. P. Srivastava and S. Ingle, “Reduction in Urbach energy and density of states for pyrite (FeS₂) thin films: healing of sulfur vacancies during hematite to pyrite transformation,” Journal of Physics and Chemistry of Solids, vol. 167, no. 7, Article ID 110753, 2022.
[20] M. Rahman, G. Boschloo, A. Hagfeldt, and T. Edvinsson, “On the mechanistic understanding of photovoltaic loss in iron pyrite solar cells,” Advanced Materials, vol. 32, no. 26, Article ID 1905653, 2020.
[21] B. Kilic, S. Turkdogan, A. Astam et al., “Preparation of carbon nanotube/TiO₂ mesoporous hybrid photoanode with iron pyrite (FeS₂) thin films counter electrodes for dye-sensitized solar cells,” Thin Solid Films, vol. 516, no. 21, pp. 7844–7850, 2008.
solar cell,” *Scientific Reports*, vol. 6, no. 1, Article ID 27052, 2016.

[22] S. Ravichandran, Y. Varthamanan, T. Elangoven, T. Elangoven, C. Ragupathi, and S. Murugesan, “Effect of polyaniline/FeS2 composite and usages of alternates counter electrode for dye-sensitized solar cells,” *Materials Today Proceedings*, vol. 49, no. 7, pp. 2615–2619, 2022.

[23] G. Velu Kaliyannan, S. V. Palanisamy, R. Rathanasamy, M. Palanisamy, S. K. Palaniappan, and M. Chinnasamy, “Influence of ultrathin gahnite anti-reflection coating on the power conversion efficiency of polycrystalline silicon solar cell,” *Journal of Materials Science: Materials in Electronics*, vol. 31, no. 3, pp. 2308–2319, 2020.

[24] Y. Zhou, A. Najar, J. Zhang et al., “Effect of solvent residue in the thin-film fabrication on perovskite solar cell performance,” *ACS Applied Materials & Interfaces*, vol. 14, no. 25, Article ID 28729, 2022.

[25] A. Weiß, G. Popov, E. Atosuo et al., “Atomic layer deposition of CaI and CsPbI3,” *Chemistry of Materials*, vol. 34, no. 13, pp. 6087–6097, 2022.

[26] K. Y. Jung, S. B. Park, and S. K. Ihm, “Linear relationship between the crystallite size and the photoactivity of non-porous titania ranging from nanometer to micrometer size,” *Applied Catalysis A: General*, vol. 224, no. 1-2, pp. 229–237, 2002.

[27] N. Yousif, E. Ouda, H. S. Magar, R. Y. A. Hassan, S. Mansour, and E.-S. M. Duraia, “Synthesis, characterization, and electrochemical sensing applications of bimetallic oxide/carbon nanomaterials hybrids,” *Journal of the Electrochemical Society*, vol. 169, no. 4, Article ID 047518, 2022.

[28] M. A. Almessiere, Y. Slimani, A. V. Thurkanov, and A. Baykal, “Structural and morphological characterization of nanomaterials,” *Synthesis and Applications of Nanoparticles*, pp. 121–137, 2022.

[29] G. V. Kaliyannan, S. V. Palanisamy, M. Palanisamy, M. Subramanian, P. Paramasivam, and R. Rathanasamy, “Development of sol-gel derived gahnite anti-reflection coating for augmenting the power conversion efficiency of polycrystalline silicon solar cells,” *Materials Science-Poland*, vol. 37, no. 3, pp. 465–472, 2019.

[30] H. Ohtsuka, M. Sakamoto, K. Tsutsumi, and Y. Yazawa, “Bifacial silicon solar cells with 21.3% front efficiency and 19.8% rear efficiency,” *Progress in Photovoltaics: Research and Applications*, vol. 8, no. 4, pp. 385–390, 2000.

[31] F. Rubio, J. Denis, J. Albella, and J. Martinez-Duart, “Sputtered Ta2O5 antireflection coatings for silicon solar cells,” *Thin Solid Films*, vol. 90, no. 4, pp. 405–408, 1982.

[32] S. Dubey, J. N. Sarvaiya, and B. Seshadri, “Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world-A review,” *Energy Procedia*, vol. 33, pp. 311–321, 2013.

[33] Y. H. Song, S. J. Kim, K. I. Choi, and T. Yamamoto, “Effects of adsorption and temperature on a nonthermal plasma process for removing VOCs,” *Journal of Electrostatics*, vol. 55, no. 2, pp. 189–201, 2002.