Performance Computation of Modified Spin Coater via Taguchi Method for Coating of Solar Cells for high speed optical Networks

S. Heeravathi
Saveetha Engineering College
Ananthi Christy (jencychristy@yahoo.com)
Saveetha School of Engineering

Research Article

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Abstract

Spin coating was used to produce thin coatings on moderately flat substrates. The coating material solution was dumped onto the substrate and turned off at a high velocity in the range of 1000–8000 rpm, leaving a uniform layer. The ultimate thickness of the deposited film was determined by the angular speed, solution viscosity, and spinning time. The advantages of spin-coating include the ability to achieve very fine, fine, and uniform coverage; however, the problem with large samples is a drawback. In this paper, we propose a fine-tuning technique for a modified spin-coating device to coat a zinc oxide (ZnO) solution on a solar cell for increasing the efficiency of the solar cell. We examined nine samples prepared using different parametric conditions, such as the spinning speed, spinning time, and quantity of solution. The spinning speed was set as 1000, 1500, and 2000 rpm. Increasing the evaporation rate instantly in the spin coater resulted in a smooth and uniform thin film. The surface of the layer and the availability of the solution were examined using scanning electron microscopy. To determine the optimal process parameters of the spin coater, the Taguchi method was used. By studying the main effects plot of the signal-to-noise ratio, the optimal settings of the parameters were obtained: a spinning time of 3 s, spinning speed of 2000 rpm, and ZnO solution quantity of 5 μL yielded the desired thickness of 2.4 μm and good uniformity. The experimental results, process parameters, and response parameters were investigated via an analysis of variance. After the solar cell was coated with the modified spin-coating device, its efficiency was 5.4%.

1. Introduction

Owing to its material and cost efficiency, thin-film technology is the most support of the current technology for smart materials. Thin films have industrial applications such as electronic semiconductors (particularly solar cells), optical coatings, and sensors owing to their pyroelectric coefficient, dielectric constant, dielectric loss, and dielectric tunability [1].

A thin film is a material layer whose thickness ranges from the nanoscale to the microscale. Thin films are widely used in electronic semiconductor devices and optical coatings. The household mirror, which characteristically includes a thin metal coating on the back of a sheet of glass to generate a reflective surface, is a well-known application of thin films. Thin-film batteries are manufactured using thin films. Thin-film technology can also be used in dye-sensitized solar cells [2].

Nanotechnology and nanoscience advancements have enabled the fabrication of functional nanoscale electronic devices made of thin sheets [3]. There are numerous ways to deposit these films, including spray pyrolysis, dip coating, doctor blades, and (most notably) the spin-coating process. These methods have potential for application in a wide range of industrial sectors, as well as technological and economic benefits [4, 5].

Spin coating was used to form thin films on substrates. The main parameters for the thin-film coating were the spinning speed, spinning time, solution viscosity, and evaporation rate. Owing to their elements, such as rotation, speeding up control, speed, and time, all of which are regulated by electronic circuits, industrial spin coaters can add large acquisition values [6].

A low-cost sol-gel spin-coating technique was used to create nano ZnO thin films using a non-vacuum method. The films obtained were translucent and consistent and adhered well to the substratum. Moreover, their surfaces had no fissures or vacuums. X-ray diffraction results confirmed that the ZnO thin films were nanostructured. The Taguchi method is a statistical strategy for identifying the control parameters that yield the optimal process results. A sequence of tests were conducted using orthogonal arrays (OAs). The results were used for the analysis of information and the projection of the quality of the produced components [7]. The main objective of this study was to make the spin-coating device more efficient, simple, and cost-effective. The spin-coating device was modified to coat a solar cell with a ZnO solution for improving its efficiency.

2. Literature Survey

In this section, we review previous studies on spin coating, which were helpful for modifying the spin-coating device.

Siddhant et al. [8] investigated thin-film spin-coating control parameters such as the spinning speed, annealing temperature, spinning time, and assembling time, and the response parameter of the bandgap was subjected to an analysis of variance (ANOVA). Nithi et al. [9] used Taguchi's design of experiments (DOE) to identify suitable conditions for spin-coating photoresist films with regard to economic cost. The optimal parameters for spin coating of the photoresist Clariantz AZ-P4620 were as follows: 13 s at a pressure of 2.5 bar and a spinning speed of 100 rpm. The dominant process parameter of the spin coating was the air velocity.

Savarimuthu et al. [10] prepared on glass substrates by simple sol-gel turn covering of straightforward leading indium oxide (In_2O_3) slim film and portrayed by X-beam diffraction, resistivity and corridor impact estimation, and optical transmission, scanning electron microscopy (SEM) picture for their primary and morphological properties. Akash et al. [11] fabricated perovskite thin films using a single-step spin-coating system and indicated the properties of solar photovoltaic applications.

Tyna et al. [12] described the spin-coating theory technique and fabricated a spin-coating machine using affordable components. Huan et al. [13] investigated spin coating on a spherical surface with a large central angle and proposed a solution to this problem. Mohammad et al. [14] fabricated economical mechanical and electrical parts based on an open-source Arduino miniature regulator. The turn coater was tested for covering the polydimethylsiloxane polymer in the turn speed range of 1000–9000 rpm. Owing to its light weight, small size, minimal effort, and great execution, it is generally suitable for use in the laboratory and in a homeroom setting. Lin et al. [15] determined that an oxidation cycle occurs during the redox capability of the stannous ingestion layer and proposed two methodologies (precious stone settling and recrystallization innovation) to reduce the oxidation cycle.

Yofentina et al. [16] examined the impact of the rotational speed in turn-covering measures for developing B2T meager films. It was discovered that speeding up the stored material in the Si substrate diminished. Halin et al. [17] fabricated a Cu_2O thin film using a sol-gel turn-covering strategy with polyethylene glycol and ethylene glycol, which can be utilized for photographic electro-compound sun-based cells. Generally, the spin coater produces films of different thicknesses with defects owing to a stronger centrifugal force. Hence, the process parameters of the spin coater must be optimized to achieve a uniform film thickness. All of the aforementioned researchers performed spin coating using expensive machines, whereas we fabricated a portable spin-coating machine and conducted a quality optimization process with consideration of the cost[24].

3. Proposed Methodology

In this study, we modified the spin-coating device to coat a ZnO solution on a solar cell for enhancing its efficiency. Initially, zinc acetate hydrate, methoxyethanol, and monoethanolamine solutions were stirred on a hotplate at a temperature of 75°C. After 150 min, the solution became milky, and after another 24 h, it became clear and transparent. Finally, we obtained the ZnO solution, which was injected into the solar cell through a micropipette. The motor speed was increased from the initial level to 2000 rpm. This process was performed thrice. To obtain a thin-film coating on the solar cell, it was dried. During the coating process, vibration occurs; thus, a vibrometer was used to analyze the vibration of the coating machine. The motor speed was controlled using the subsynchronous resonator (SSR) model. A thermocouple was used to maintain a constant temperature. The annealing process was performed in a separate oven. After the annealing process, a vacuum pump was used to remove the moisture inside the drum. In this modified device, a heating unit was fabricated for the drying process, which provides the required heat through a blower gun. This increases the evaporation rate, leading to smooth and uniform film layers. The Taguchi DOE is widely used to reduce the occurrence of defects and failures in the production of goods. It improves the quality and reduces the number of experiments required. Higher values of the signal-to-noise ratio (SNR) find control factors and minimize the effect of noise.

The results of the experiments were converted into the Taguchi S/N, and the optimal parameters were obtained. ANOVA statistics were used to determine the contribution rates of the components. The target film thickness of 2.4 μm was achieved with good uniformity for the production of solar panels using the proposed spin-coating device.

3.1 Spin coater

The spin-coating process uses the principle of centrifugal force. When the disk is rotated in any direction, a centrifugal force is generated, which draws the rotating body away from the center of rotation. The spin coater is fabricated according to the requirements of the thin-film thickness of the solar panel. The spin-coater modeling is shown in Figs. 1 and 2. Many parameters affect the film thickness. In this study, the evaporation rate is considered as an important factor. Typically, an annealing process, which is also called the evaporation rate, should be performed on the coated substrate. The annealing process was performed in a separate oven. When the substrate is placed in an oven, the atmospheric pressure or temperature affects the layer [18]. In the modified device, a heating unit was fabricated for the drying process, which provides the required heat through a blower gun. This increases the evaporation rate, leading to smooth and uniform film layers.

Table 1
Specifications of the fabricated spin coater

Materials	Rating
Spinning speed	800 rpm (max)
Motor rating	220 V
Mode	Programmable Human Interface
Speed controller used	SSR
Spin plate	6 mm
Material	Acrylic
Size of pipette	0.5 mm

3.2 Coating material

In this study, the coating material was a zinc oxide (ZnO) solution, which is a highly conductive medium. The preparation of the ZnO solution is described in detail in the following subsection.

3.3 Preparation of ZnO solution

The most common semiconductor compounds are ZnO and titanium dioxide (TiO_2) [19]. ZnO has a higher conductivity than TiO_2 [20]. In this experiment, a ZnO solution was used to coat the solar panel. Zinc acetate hydrate was used as a starting material, methoxyethanol was used as the dissolvent, and monoethanolamine was used as a stabilizer. These three solutions were stirred on a hotplate at 75°C for 150 min, yielding a milky solution, which was then kept for 24 h to let it become clear. Figure 3 shows a flow diagram of the preparation of the ZnO solution. Following the preparation of the ZnO solution, the coating was injected using a micropipette. The motor speed was increased to 2000 rpm. This process was repeated thrice. To obtain a thin-film coating on the solar cell, it was dried. A thermocouple was used to maintain a constant temperature. After the annealing process, the moisture inside the drum was removed using a vacuum pump. As shown in Fig. 4, the ZnO solution was prepared using a magnetic stirrer with a hotplate.

3.4 Characteristics of thin film

In thin-film coating[22], the thickness of the ZnO layer was measured via SEM according to the cross section of the layer, and the surface of the layer was also examined. The presence of ZnO was confirmed using an energy-dispersive detector[23]. Figure 5 shows the surface of the thin-film layer after the annealing process. The grey color indicates the growth of crystals in the solution. Figure 6 shows the ZnO layer, with the yellow dots representing the atoms in the ZnO.

3.5 Taguchi DOE

DOE is an important method for determining the relationships between the factors affecting a process [21]. The Taguchi DOE is widely used to reduce the occurrence of defects and failures in the production of goods. It improves the quality and reduces the number of experiments performed. Higher values of the SNR find control factors and minimize the effect of noise.

The three parameters examined in this study were the spinning speed, spinning time, and quantity of solution. Three levels were used for each experimental parameter. The three levels of the spinning speed were 1000, 1500, and 2000 rpm. The spinning times were 3, 6, and 9 s, and the solution quantities were 3, 4, and 5 μL. The process parameters, levels, and factors of the spin coater are presented in Table 2. Here, three parameters and three levels are given, and there is no interaction among the parameters. Therefore, in the experiment, an L9 OA was utilized to find a smaller film thickness of the spin coater, as shown in Table 3.

Table 2
Spin-coating process parameters, levels, and factors

Parameter	Unit	1	2	3
Spinning speed	rpm	1000	1500	2000
Spinning time	s	3	6	9
Quantity of solution	μL	3	4	5

Table 3
Spin-coating process parameters

Experiment number	Spinning speed (rpm)	Spinning time (s)	Quantity of solution (μL)
1	1	3	3
2	1	6	4
3	1	9	5
4	2	3	4
5	2	6	5
6	2	9	3
7	3	3	5
8	3	6	3
9	3	9	4

3.6 ANOVA

ANOVA is a method that is utilized to find significant differences between two or more independent variables. It is a statistical test that generalizes the t-test with means. The F-test of by and large criticalness demonstrates whether the direct relapse ideal gives a preferred fit to the data over a model that holds no autonomous factors. The optimized process parameters of the spin coater were subjected to an ANOVA.

3.7 SNR analysis

In the Taguchi approach, the SNR was employed to optimize the coating conditions. In the analysis of the SNR, the optimal parameter was utilized to optimize the ZnO value of the coatings. This resulted in SNR optimization of the sol-gel process for coating metallic substrates. The average % of coated area figures for the nine experimental settings are shown here.

$$S/N = -10\mathrm{Log}\left[\frac{1}{n}\left(\sum_{i=1}^{n}\frac{1}{y_i^2}\right)\right]$$

Here, y_i represents the value of the quality characteristic, and n represents the number of measurements in each experiment.

4. Results And Discussion

A target film thickness of 2.4 μm was achieved with good uniformity for the production of solar panels using a spin coater. With the given target, a higher SNR was selected for analysis. After the parameters were set, nine iterations were performed. The mean SNR was calculated for each parameter at each level. The optimal parameters for the spin coating of solar cells were as follows: a spinning speed of 2000 rpm, spinning time of 3 s, and solution quantity of 5 μL, which yielded the smallest film thickness of 2.4 μm, as shown in Table 4. Figure 3 shows the main effects plot for the spin-coating parameters for the solar cell. The spinning speed exhibited the highest SNR, and it represented the 2nd level of the spinning time, 1st level of the spinning speed, and 3rd level of the quantity of solution.

Table 4
Spin-coating process parameters for the solar panel

Experiment number	Spinning speed (RPM)	Spinning time (s)	Quantity of solution (μL)	Film thickness (μm)
1	1000	3	3	2.9
2	1000	6	4	2.6
3	1000	9	5	2.5
4	1500	3	4	3.5
5	1500	6	5	3.6
6	1500	9	3	2.8
7	2000	3	5	2.4
8	2000	6	3	3.6
9	2000	9	4	3.2

Figure 7 shows the main effects plot for the modified spin-coating parameters. The parameter between the mean SNR and the spinning speed, spinning time, and quantity of the solution.

Table 5
Response table for the spin-coating parameters

Level	Spinning speed	Spinning time	Quantity of solution
1	−13.05	−13.40	−13.67
2	−13.98	−13.79	−13.57
3	−14.57	−14.41	−14.40
Difference	1.53	1.01	0.88
Rank	1	2	3

Table 5 presents the response table and indicates that the spinning speed was an influencing (Rank 1) process parameter for the spin-coating of the solar panel. The average value of the SNR was calculated from the differences between the SNR values of the parameters. Among the three parameters, the spinning speed had the highest SNR. This is the main parameter that affects the thickness of thin films on solar cells.

From the ANOVA, at a 95% confidence level is shown in Table 6. Here, DF represents the number of degrees of freedom, MS represents the mean square, F represents the difference in the variance, and P represents the probability of obtaining results. This indicates that nil parameters have an impact on the average film thickness with the significance and impact of all parameters, and the impact of the spin coater is the 2nd level of the coating time, 1st level of the spinning speed, and 3rd level of the solution. Thus, higher values of F are beneficial for achieving a thinner film.

Table 6
ANOVA for the spin-coating parameters

Source	DF	Adj. MS	Adj. MS	F-Value	P-Value	% contribution
Spinning speed	2	1.1467	0.5733	1.67	0.375	42.47
Spinning time	2	0.4467	0.2233	0.65	0.606	16.54
Quantity of solution	2	0.4200	0.2100	0.61	0.620	15.55
Error	2	0.6867	0.3433	-	-	25.43
Total	8	2.7000	-	-	-	100.00

Figure 8 presents the interaction plot for the spin-coating process of the solar panel. As shown, the spinning speed, spinning time, and quantity of solution were independent parameters of the spin-coating process.

Figure 9 presents the contour plot (three-dimensional view) for the spin-coating process parameters of the solar panel. As shown, the minimum film thickness was obtained at the first level of the spinning time (3 s).

4.1 Vibration analysis

Vibration may occur during the operation of the device. Heavy vibrations adversely affect the device and the particle concentration, thereby deteriorating the thin film. This affects the film uniformity and thickness. In this experiment, we used a vibrometer sensor to analyze the vibrations of the device at different speeds: 2000, 4000, and 8000 rpm. Figures 10–12 present the vibrations at the different speeds.

Table 7
Performance analysis of the modified spin-coated solar cell

Voc (v)	Isc (mA)	FF	Efficiency
0.49	16.7	0.67	5.4

Figure 13 and Table 7 present the performance of the ZnO-coated solar cell fabricated using the modified spin-coating device with regard to the electrical conductivity. The proposed spin-coating device has a low cost and improved the efficiency of the solar cell.

5 Conclusion

We designed a modified spin-coating device using different materials and technical methods. The fabrication process of the modified spin-coating device was clearly explained. We used a ZnO solution, which had a high conductivity, as a coating material for a solar cell. We experimented with different process parameters, i.e., the spinning speed, spinning time, and quantity of solution. The Taguchi DOE was used to identify the optimal parameters, which were a spinning speed of 2000 rpm, spinning time of 3 s, and solution quantity of 4 μL. In this condition, the minimum film thickness of 4.2 μm was obtained. In the experimental analysis, when the spinning speed increased, the film thickness decreased. Therefore, the spinning speed is an important parameter for reducing the film thickness. A contour plot was used to analyze the thickness of the film. After the ZnO solution was coated on a solar cell, an efficiency of 5.4% was achieved. Compared with the existing spin-coating device, the modified device achieved a higher efficiency of 5–10%, respectively. This modified spin-coating device represents the fastest and simplest method for producing microfilm coatings of ZnO solutions on solar cells. The results of this study can be used for further production of solar panels via the modified spin-coating method. However, other aspects, such as the processing speed, are still lower for the scan coating than for the spin coating. We want more changes to achieve high-efficiency and low-thickness coating systems in the future.

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Figures

Figure 1

Modeling of the spin coater

Figure 2

Fabricated spin coater

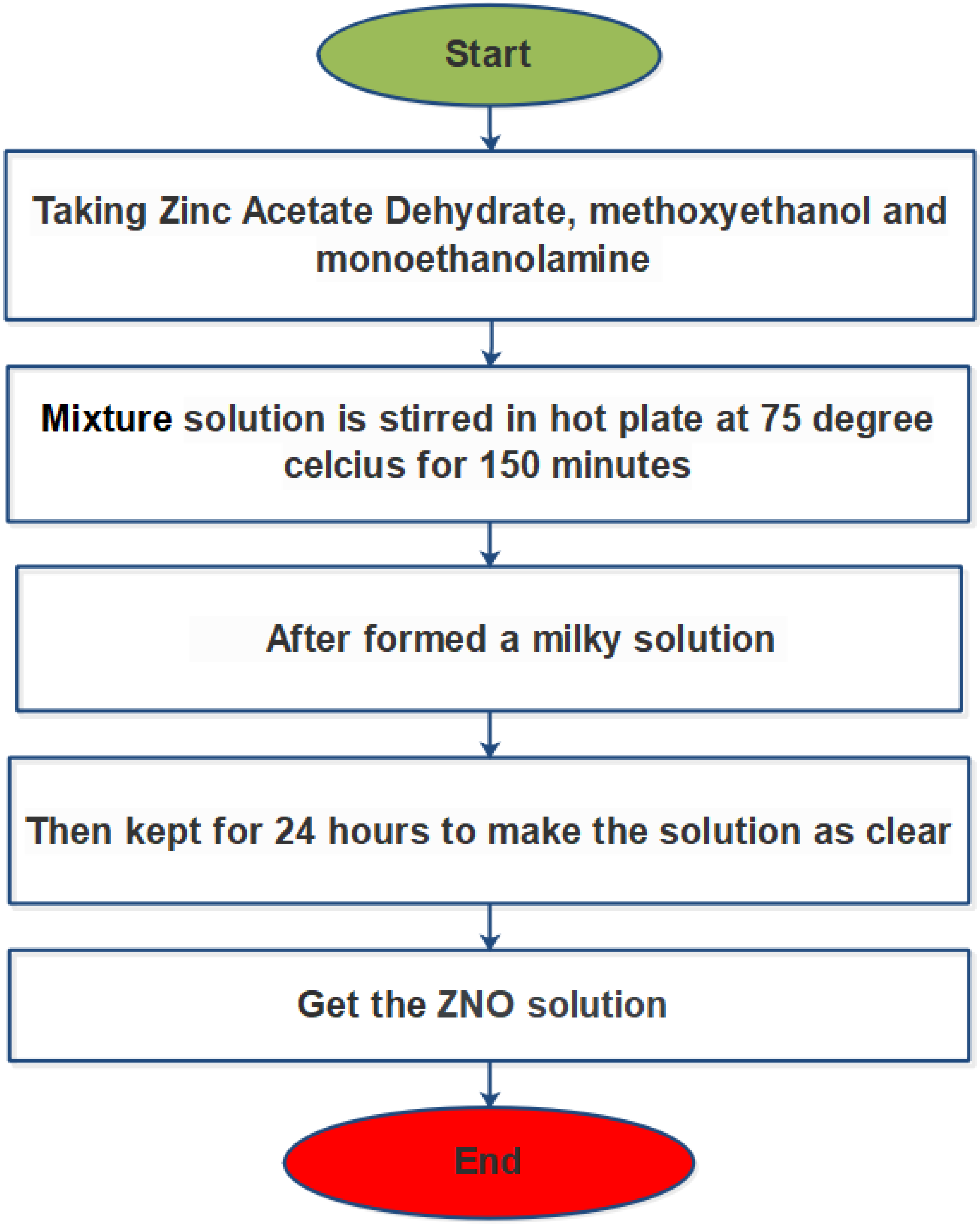

Figure 3

Flow diagram of ZnO solution preparation

Figure 4

Prepared ZNO solution in the magnetic stirrer

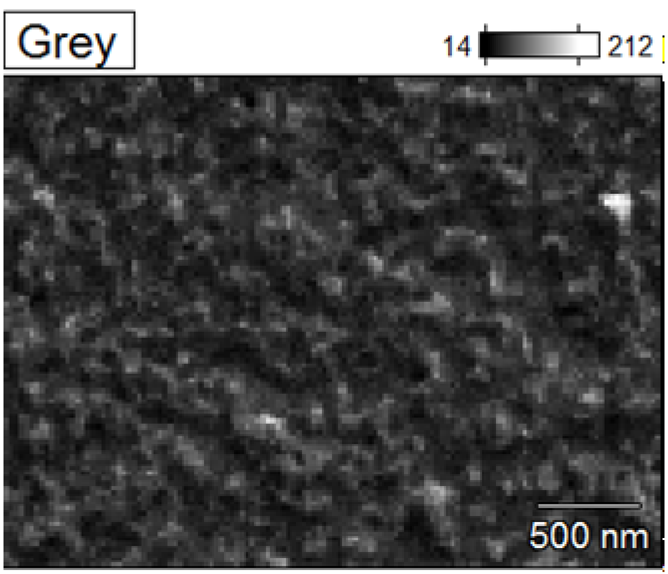

Figure 5

SEM image of the ZnO surface

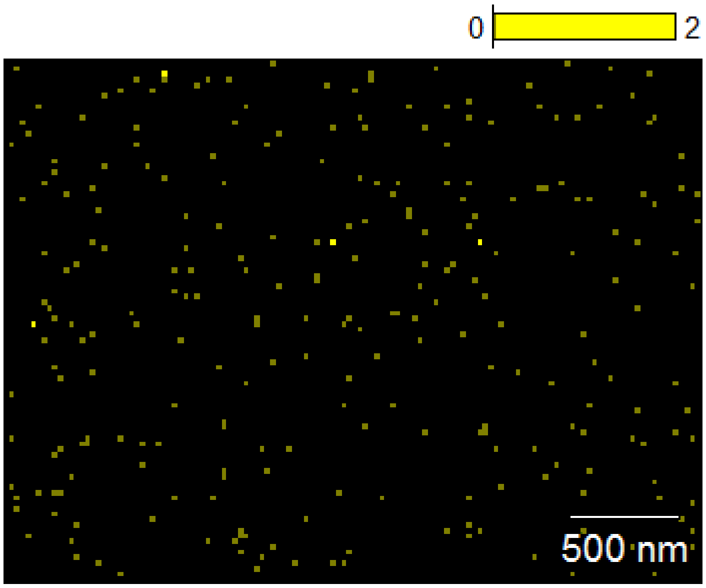

Figure 6

SEM image showing the presence of ZnO

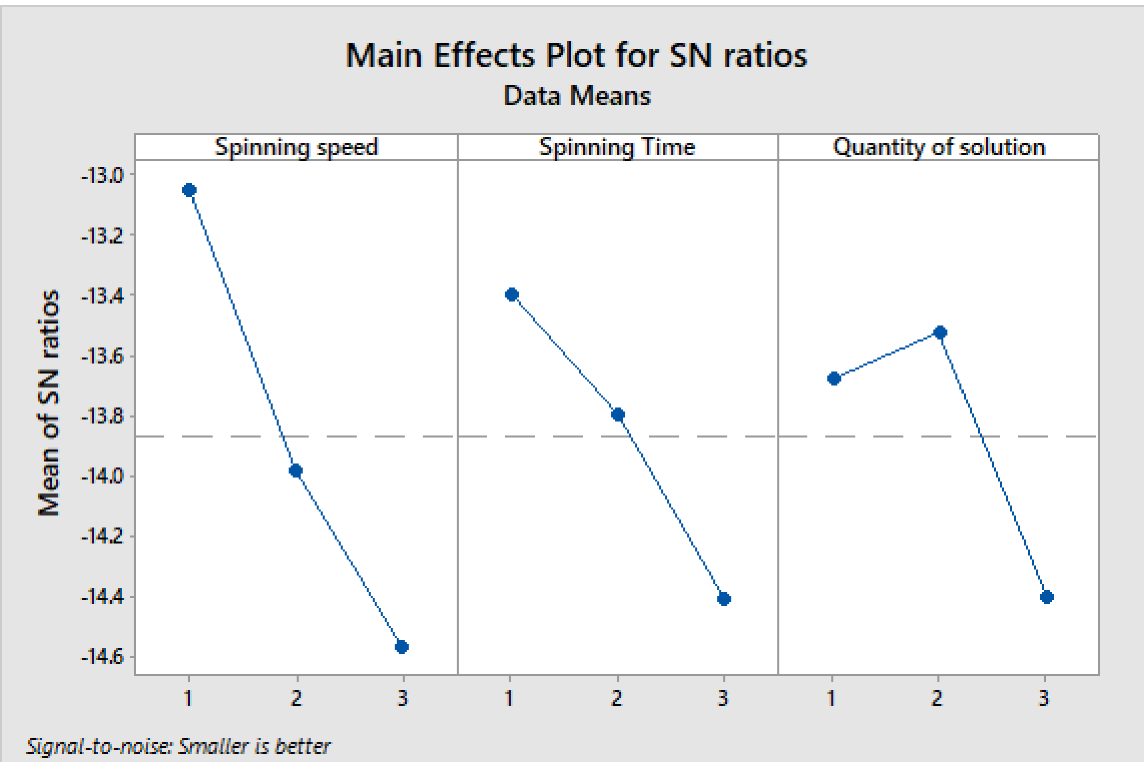

Figure 7

Main effects plot for the spin-coating parameters

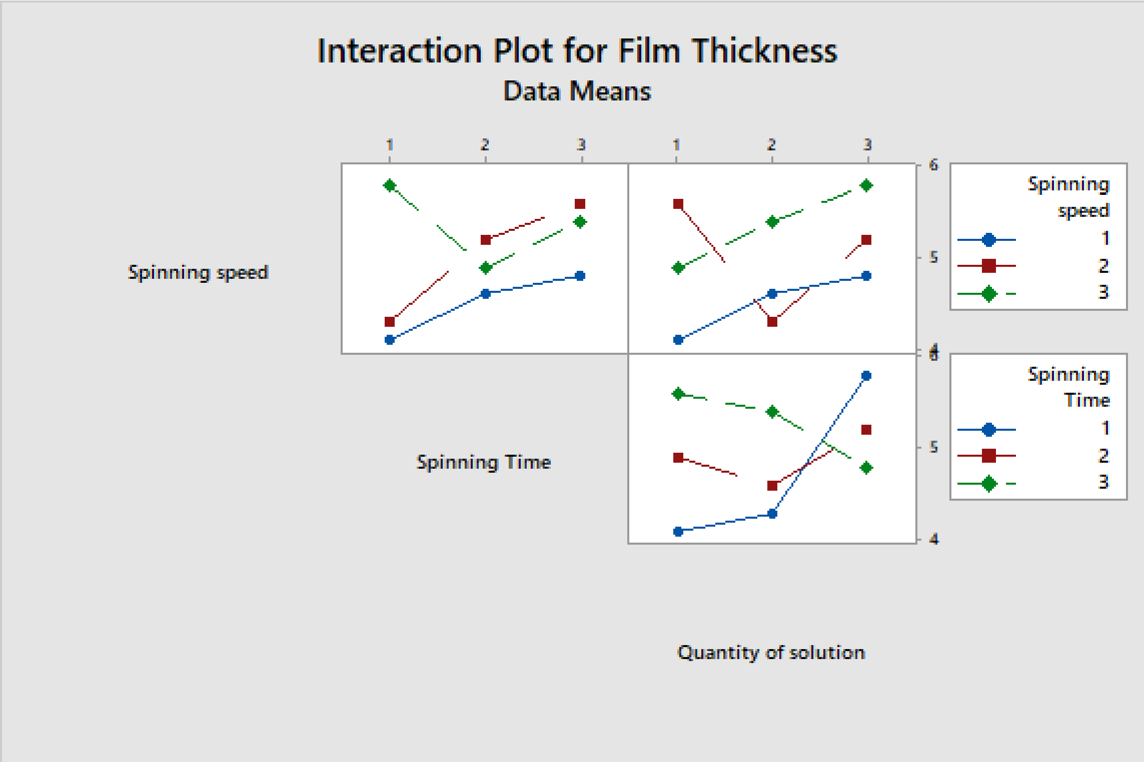

Figure 8

Interaction plot for the spin-coating process parameters

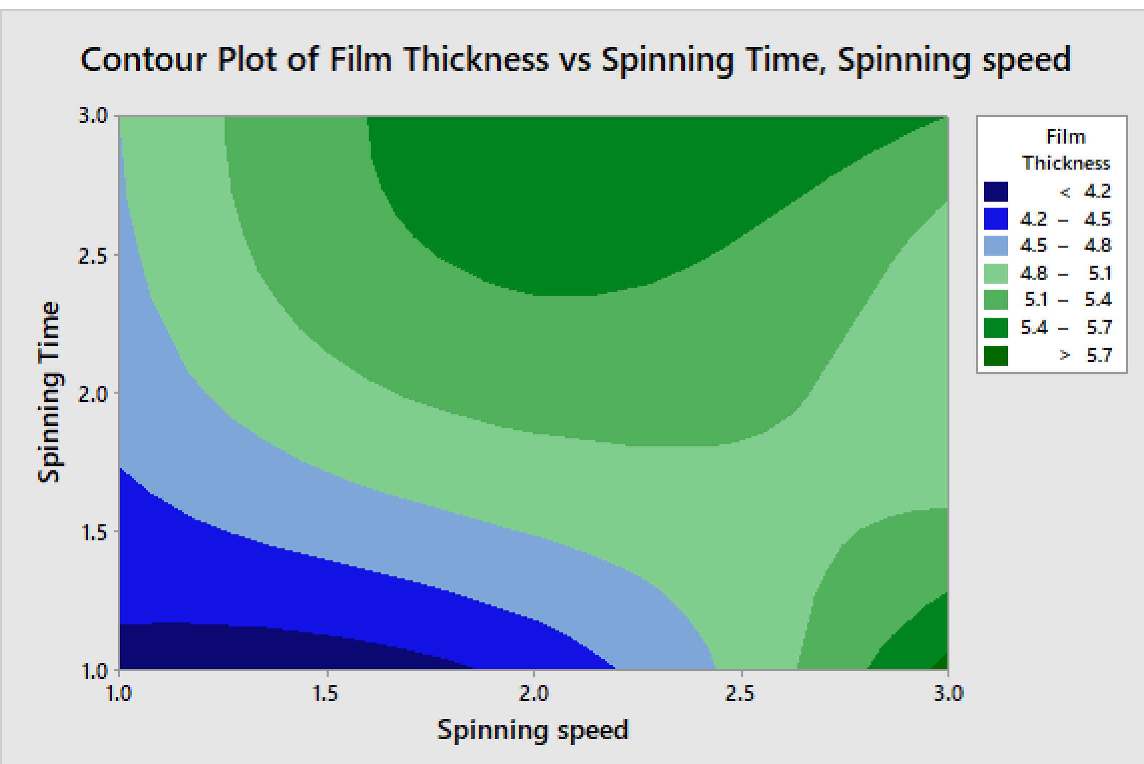

Figure 9

Contour plot for the spin-coating process parameters

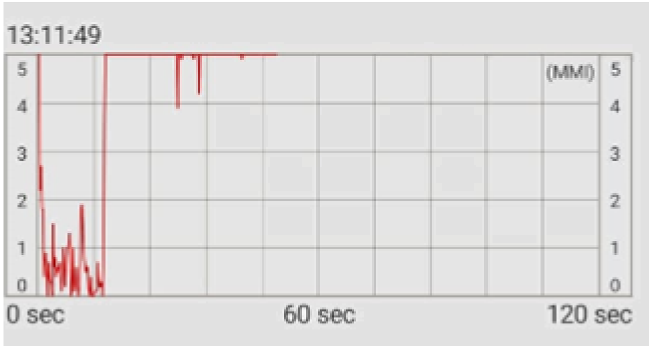

Figure 10

Vibration analysis at 8000 rpm

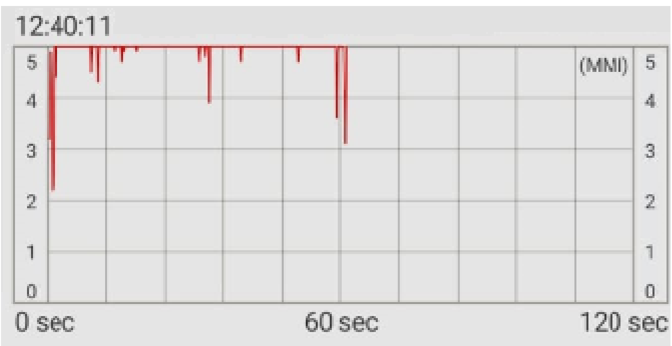

Figure 11

Vibration analysis at 4000 rpm

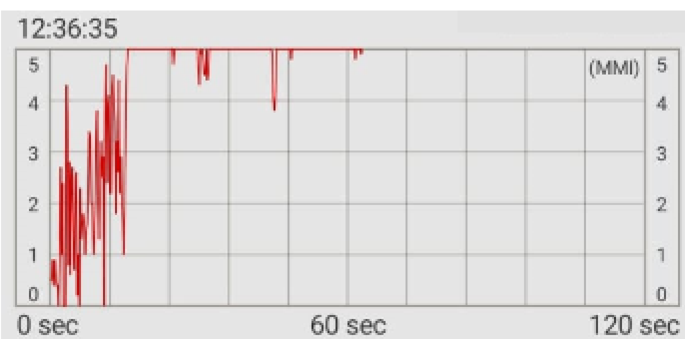

Figure 12

Vibration analysis at 2000 rpm

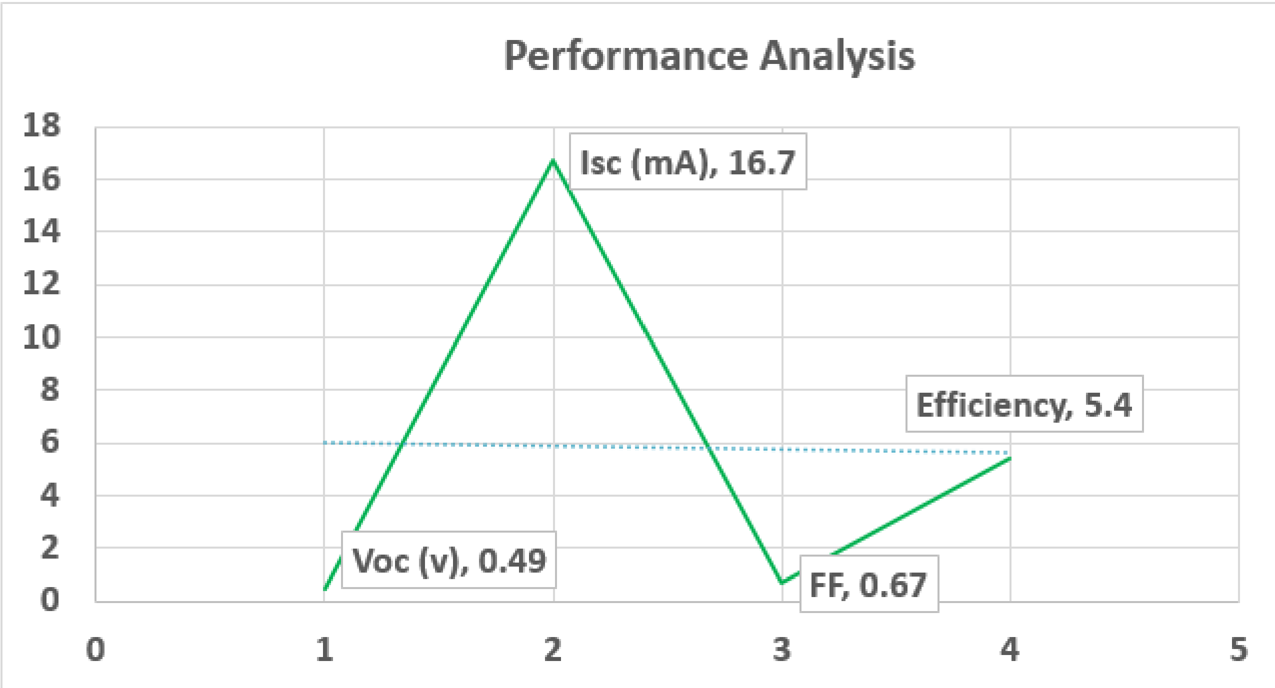

Figure 13

Efficiency of the ZnO-coated solar cell