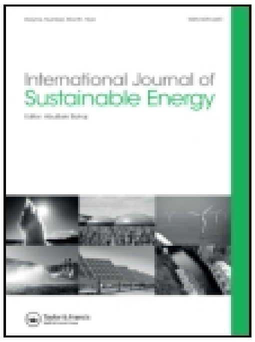

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Efficiency improvement on the multicrystalline silicon wafer through six sigma methodology

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Crystalline silicon solar cell technology continues to be dominant in the photovoltaic (PV) technology due to its novel process flow and the clear understanding of the material. Being a mature material-based technology; on the one hand, it has quite a few opportunities for improvement, on the other hand, the expansion of solar energy should depend on this technology. Due to increase in the global energy consumption and high competition level in the market, it has become necessary to show significant improvement in the performance of the present process/product. The demand for high efficiency solar cells at low costs with shorter cycle times forced the manufacturing industries to improve their processes by applying systematic methodologies such as Six Sigma. This paper illustrates the importance of anti-reflective coatings (ARCs) on the silicon solar cell processes and the successful implementation of Six Sigma to improve the efficiency of the silicon solar cells. The different phases of the Six Sigma DMAIC approach applied to the process and the results are interpreted.

Keywords: solar cells; crystalline silicon; efficiency improvement; Six Sigma; Taguchi method; signal-to-noise ratio

1. Introduction

Crystalline silicon technology has been the leading technology for the solar cell production in the past two decades and this trend is expected to continue (Bruton 2002; Möller *et al.* 2005; Popov 2000; Gerhard 2004). Currently more than 90% of all commercial solar cells are made from silicon (Müller *et al.* 2006). The advantages of silicon technology are the matured processing technology, the large abundance of the silicon in the Earth and its non-toxicity (Green 1995). Among the different kinds of solar cell process technologies such as screen printed solar cells (Lipiňski *et al.* 2003; Mouhoub *et al.* 2003), buried contact cells (Ben Rabha *et al.* 2006), solar cells on silicon ribbons (Miles 2006), etc., screen printed solar cells are the most commercially available technology. Screen printed solar cells attracted the attention of many industries due to its specific significances such as simple, robust, continuous and easily adaptable process (Lipiňski *et al.* 2003; Mouhoub *et al.* 2003). Typical efficiency of the screen printed solar cells lies in the range

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15–18% for mono crystalline and 14–17% for multicrystalline silicon cells. Since the efficiency of the cell influences the production cost, a continuous extensive effort are being attempted towards the efficiency improvement. The required near-future efficiency targets for industrial solar cells are 18–19% and 16–18% for mono and multicrystalline silicon, respectively. Based on the present efficiency trends in the industry, one can consider that the solar cell manufacturers are able to fulfill the efficiency goal by tuning the processes involved in the screen printed solar cell process flow (Lipiňski *et al.* 2003). The conventional process steps in the screen printed solar cells are as follows.

- Front surface texturing.
- Doping profile.
- Anti-reflective coatings (ARCs).
- Front contact and drying.
- Back surface passivation (oxide/nitride passivation).
- Back pad and back surface field.
- Drying and cofiring.

In order to fabricate high efficiency solar cells, it is important to optimize any one of the processes in the conventional process steps. Among all the processes, ARCs is one such a critical process that helps to reduce the reflection and to increase the passivation. The PV industries use different materials such as silicon nitride (SiN), silicon oxide (SiO_2) and titanium oxide (TiO_2), etc as ARCs (Zhao and Green 1991; Chen *et al.* 1993). In the group of materials, thin films of silicon nitride (SiN) attracted the attention of industries/researchers for ARCs (Henning *et al.* 1999; Soppe *et al.* 2005) in silicon solar cells due to their optical properties which can be tailored during deposition to match those of Si solar cells. For PV applications, SiN is usually deposited from the gas mixture of Silane and Ammonia. Silane acts as silicon and hydrogen source whereas ammonia being a source of nitrogen, has a tendency to deposit SiN with a high ratio of incorporated hydrogen. The plasma-enhanced chemical vapour deposition (PECVD) technology in the production of mc-silicon solar cells is spreading in these years because it shows considerable improvement in solar cell efficiency (Kumar 2005). The important driving forces behind the enhancement are as follows.

- Large quantity of hydrogen originating from plasma gas dissociation and incorporated in the silicon nitride film can be driven into the solar cell during metallization, which leads to an excellent bulk passivation. Ultimately around 1–1.5% of efficiency increment can be achieved due to the hydrogenation of defects in the mc-Si wafers.
- Secondly surface passivation effect. Silicon nitride films provide the very low surface recombination velocities both on phosphorous-diffused regions and on p-type as well.
- Finally the SiN coatings reduce the light reflection considerably.

Hence, SiN deposition by PECVD is a common method to combine bulk and surface passivation for ARC in order to improve the solar cell electrical characteristics (Soppe *et al.* 2005). Two types of PECVD methods used are remote and direct PECVD. This study has been dealt with direct PECVD.

The high efficiency silicon solar cells at low costs with shorter cycle time can be achieved by considering the various new product design, manufacturing/ management strategies was implemented by many PV industries. Several process improvement methodologies are available in literatures and organizations/industries adopt these methods for improving their processes and products. Six Sigma is a systematic methodology aims at operational excellence through continuous process improvements (Pande *et al.* 2003).

This paper deals with the importance of direct PECVD process and the successful application of Six Sigma methodology to improve the efficiency through PECVD. The different activities carried out as per various phases of six sigma methodology are explained.

2. Background

2.1. *SiN deposition using PECVD*

Available literatures on ARCs reporting that the bare silicon–air interface reflects 35% of the incident AM 1.5G spectrum, which was not appealing for the fabrication of high efficiency solar cells commercially. Industrial silicon solar cells use either alkaline texturisation or isotropic etching and ARCs for restricting the reflection. PECVD is generally considered as a processing technique for ARCs because of the high throughput rates. The optical properties of ARC can be tailored by changing the process parameters such as gas flows, deposition rate, etc. Apart from the single layer ARC (Henning *et al*. 1999), researchers developed dual layer (Kumar *et al*. 2005) and multilayer ARCs for the solar cells. Optical properties of the ARC are one of the important factors for the reflection losses in solar cells. Hence thickness and refractive index of the SiN coatings are chosen such that the solar cell gives maximum internal quantum efficiency (IQE). In addition to anti-reflection properties, SiN films contain large quantity of hydrogen. During the high temperature process some of this hydrogen move towards the underlying silicon, leads to an improvement of the bulk carrier life time i.e. hydrogen passivation of bulk defects. Due to these two properties SiN acts as a surface and bulk passivating ARC on crystalline Si, a unique combination that is not available in other ARCs for c-Si solar cells (Chen *et al*.1993; Soppe *et al.* 2005; Kumar *et al.* 2005).

2.2. *Six Sigma*

Six Sigma is a well-structured methodology that focuses on reducing variation, eliminating defects and improving the quality of products, processes and services (Breyfogle III 1999). Six Sigma methodology was originally developed by Motorola in 1980s and it targeted a difficult goal of 3.4 parts per million defects (Harry *et al*. 1999). Six Sigma has been successfully implemented worldwide for more than 20 years, producing significant savings to the bottom-line of many large and small organizations (Snee and Hoerl 2003). A number of papers and books have been published addressing the fundamentals of Six Sigma (Harry *et al.* 1999; Pande *et al*. 2000; Gijo and Rao 2005; Pande *et al*. 2003).

There are two approaches for carrying out Six Sigma projects. They are DMAIC (Define, Measure, Analyse, Improve and Control) and DFSS (Design for Six Sigma). In this study, the DMAIC method was used to improve the efficiency of multicrystalline silicon wafer. During the implementation of DMAIC methodology, quite a few statistical expressions/techniques, such as Taguchi experiment, sigma level calculation, p value, S/N ratio, etc were utilized for analysing the process data and making meaningful inferences about the process. These analyses were performed with the help of Minitab, statistical analysis software. Minitab can be used for learning about statistics as well as statistical research.

Taguchi's experimental design method is a well-known quality improvement technique for carrying out the analysis of experiments with the least experimental effort (Taguchi 1988; Ross 1996, Taguchi and Wu 1979). It has also been widely used for process optimization worldwide (Gijo and Rao 2005; Gijo and Scaria 2010). Taguchi method uses orthogonal arrays (Rao 1947) for designing the experiment and the data are analysed by considering Signal-to-Noise (S/N) ratio, as explained earlier (Taguchi 1988; Phadke 1989). The S/N ratio measures the level of performance and the effect of noise factors on performance (Wu and Hamada 2000). The higher this ratio is, the more the process is doing what it is intended to do regardless of noise factors. S/N ratios to be selected depending on the characteristics of the responses (Phadke 1989). Many industrial problems for reducing variation in the processes were addressed by considering S/N ratios of smaller-the better, nominal-the-best and larger-the-better (Gijo 2005; Gijo and Scaria 2010).

3. Process and experiment

The process dealt with direct PECVD for dual layer of SiN coatings on 12.5 cm^2 mc-Si wafers of bulk resistivity around 1.5 Ω-cm. with the thickness in the range of 180–250 μm and the process is explained in detail elsewhere (Kumar *et al*. 2005). The schematic of the direct PECVD is as shown in Fig. 1. In order to overcome the material-related variation, neighbouring wafers from the same ingot were taken for this experiment. Typical industrial process flow (Kumar *et al*. 2005) was followed for the entire experiment. Experiments were designed with the process parameters of the PECVD process with the help of Minitab statistical software and data were analysed to identify the optimum operating levels for the process parameters. The details of the study with different phases of Six Sigma methodology along with concluding remarks are presented.

4. Six Sigma approach to PECVD

The problem, improving the efficiency of multicrystalline silicon wafer, was handled by applying Six Sigma DMAIC methodology. Six Sigma explores the functional form, $Y = f(x)$, where Y is the output or result (dependent variable) of the process and x's are the causes (independent variables) which affect the output. In the present case study, Y, the critical to quality (CTQ) characteristic is an important parameter due to its significance in the efficiency of the solar cells.

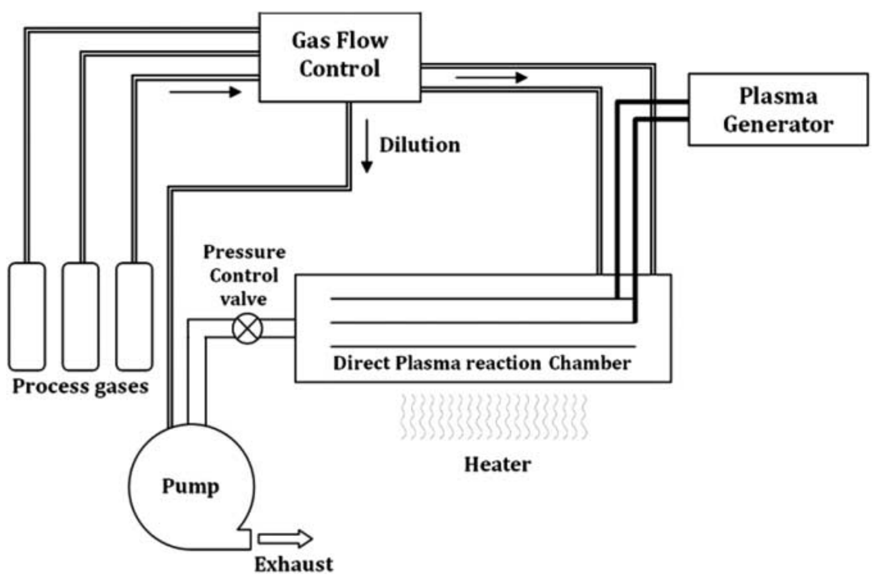

Figure 1. Schematic of the direct PECVD for SiN deposition.

The define phase of the DMAIC methodology helps to formulate the scope and goals of the project for improvement. The first step in the define phase was to develop a project charter which defines the project title, objectives, schedule, resources and expected financial benefits of the project, etc. The problem statement of this project was defined as enhancing the efficiency of multicrystalline silicon wafer. SiN coatings by PECVD is a well-known method to combine bulk and surface passivation along with ARC, which improves the solar cell electrical characteristics (Soppe *et al.* 2005) such as V_{oc}, I_{sc} and FF. After having a number of brainstorming sessions, it has been decided to look at the V_{oc} as the CTQ characteristic to enhance the efficiency of the solar cell considerably.

The measure phase involves in choosing one or more product characteristics, mapping the process, carrying out the necessary base line measurements, recording the data and establishing the base line performance of the process. After identifying the process characteristic which drives for perfection – CTQ characteristic, it is necessary to validate the measurement system by conducting a measurement system analysis (Montgomery 2002). A gage repeatability and reproducibility (G R&R) study was conducted by involving two operators from the process and it was found that the measurement system performance was adequate. A data collection plan was drafted to collect the data on V_{oc} and the input variables. The data were collected as per the plan to evaluate the baseline status of CTQ. The collected data were tested for normality using the Minitab software and is presented in Fig. 2. The data were analysed for finding the p value (p value is the probability value which judges the significance of a statistical test. The smaller the p-value leads the more significant result. Typically values below 0.05 are considered indicative of a significant test outcome.) and the value found is 0.05. Since the p value from the test is less than 0.05, it was concluded that the data from the process that is not normal. Further data were tested for all known distributions by Minitab software and failed to identify any particular distribution for this data. The process capability analysis of the running process recipe has been carried out and is shown in Fig. 3. Hence, from the observed performance of the process capability analysis (Fig. 3) the parts per million (ppm) was identified and the corresponding sigma level (Sigma level is a quality level calculated to describe the capability of a process to a specification. It is a measure which compares process variability with the requirements. A process with Six Sigma quality level is said to have 3.4 defects per million opportunities.) was estimated as 2.67. The estimated sigma level from

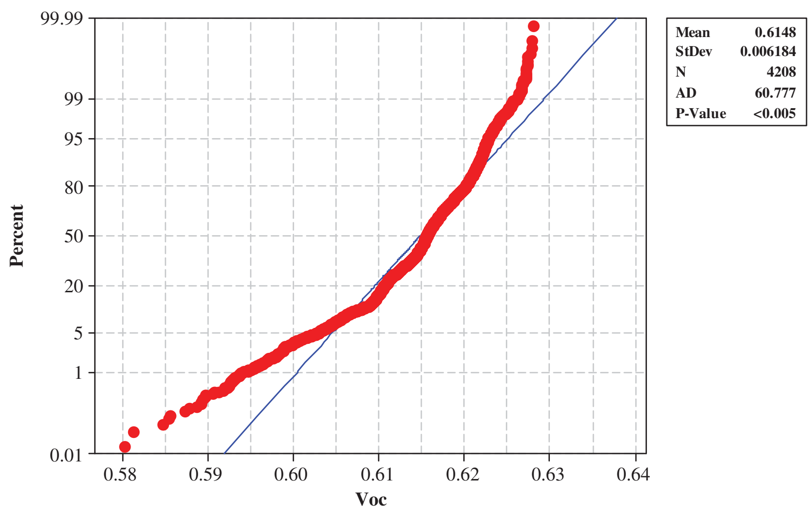

Figure 2. Normal probability plot of V_{oc}.

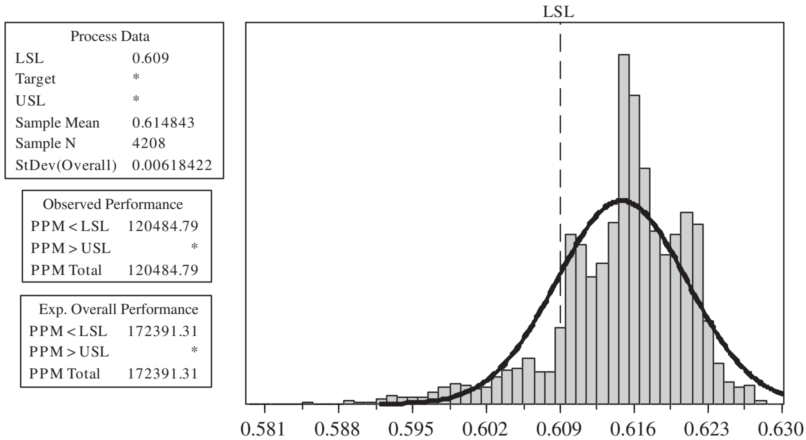

Figure 3. Process capability analysis on V_{oc}.

Fig. 3 reveals that the process can be improved further to achieve higher V_{oc}, the CTQ of the project.

The objective of the analyse phase is to identify the root causes of the problem, so that improvements can be achieved in the process. The first step towards identifying the root causes is identification of potential causes. After a brain storming session, the potential causes were identified for low V_{oc} of the PECVD process and presented in the cause and effect diagram as shown in Fig. 4. All the causes listed in the cause and effect diagram were validated based on the cause validation plan presented in Table 1. Out of all causes listed in the cause and effect diagram, few causes were validated through GEMBA (Work place investigation) and it was found that these

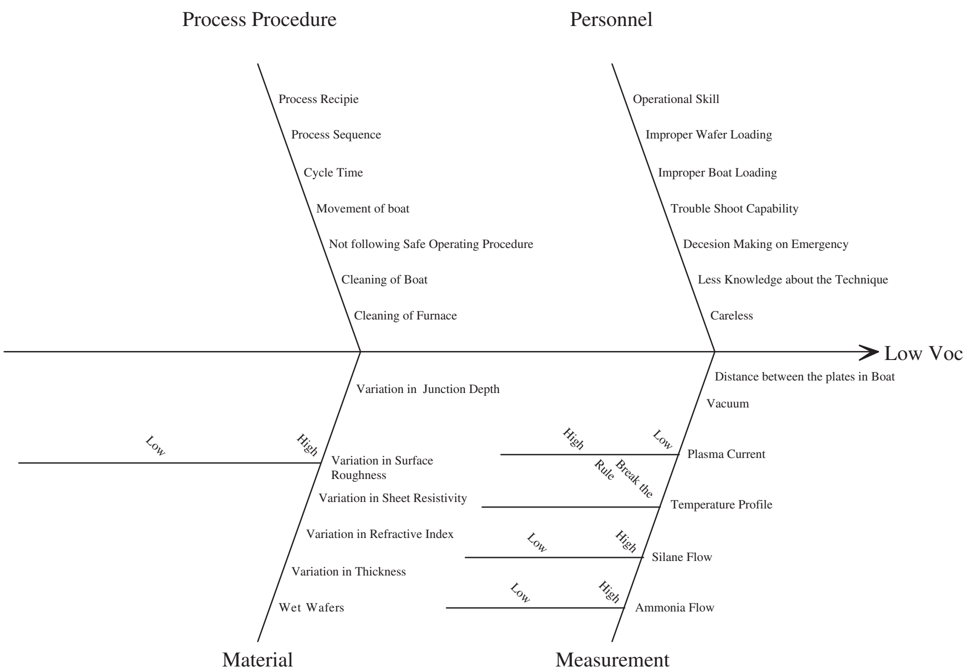

Figure 4. Cause and effect diagram for low V_{oc}.

Table 1. Cause validation plan.

	Causes	Validation method
Personal	Unskilled operation	GEMBA
	Improper wafer loading	
	Improper boat loading	
	Lack of trouble shoot capability	
	Lack of decision making on emergency	
	Lack of technique	
	Careless	
Process procedure	Not following the optimized process Recipe	GEMBA
	Not following the process sequence	GEMBA
	Improper cycle time	
	Improper movement of boat	
	Not following the safe operating procedure	
	Improper cleaning of boat	
	Improper cleaning of furnace	
Material	Wet wafers	GEMBA
	Variation in thickness	From Ellipsometer results
	Variation in refractive index	
	Variation in sheet resistivity	Four point probe measurement
	Variation in surface roughness	By using surface profiling
	Variation in junction depth	GEMBA
Process parameters	Variation in ammonia flow	DOE
	Variation in silane flow	DOE
	Variation in temperature profile	DOE
	Variation in plasma current	DOE
	Variation in cycle time	DOE
	Distance between the plates in boat	GEMBA

causes (variables) were performing as per process requirement (Gijo and Scaria 2010). The causes thickness, refractive index, sheet resistivity and surface roughness values were evaluated for one batch of wafers and were found that they are within the specification. After having a discussion, the team felt that it is necessary to optimize the process parameters such as ammonia flow, silane flow, cycle time and the RF power for improving the efficiency. Hence, it was decided to conduct a design of experiment to identify the optimum levels of factors in the improve phase so that the required improvement in V_{oc} can be achieved.

In the improve phase, the process parameters (factors) and values for process parameters (levels) were selected for conducting the experiments. As discussed in the background of this article, this experiment deals with the dual layer of SiN coating and hence for dual layer coating, different gas flows and different deposition time with same RF power were identified as factors for experimentation. It was decided by the team that each factor will be studied at three levels to understand the process variation. The factors and levels thus arrived are presented in Table 2. To conduct a full

Table 2. Factors and levels for experimentation.

		Levels		
S. No.	Factor	1	2	3
1	Silane flow Layer 1	L	M	H
2	Silane flow Layer 2	L	M	H
3	Ammonia flow Layer 1	L	M	H
4	Ammonia flow Layer 2	L	M	H
5	Time Layer 1	L	M	H
6	Time Layer 2	L	M	H
7	RF power	L	M	H

L - Low, M - Medium, H - High

Table 3. Master plan for experimentation.

	Silane flow		Ammonia flow		Time		
S.No.	Layer 1	Layer 2	Layer 1	Layer 2	Layer 1	Layer 2	RF power
1	L	L	L	L	L	L	L
2	L	L	L	L	M	M	M
3	L	L	L	L	H	H	H
4	L	M	M	M	L	L	L
5	L	M	M	M	M	M	M
6	L	M	M	M	H	H	H
7	L	H	H	H	L	L	L
8	L	H	H	H	M	M	M
9	L	H	H	H	H	H	H
10	M	L	M	H	L	M	H
11	M	L	M	H	M	H	L
12	M	L	M	H	H	L	M
13	M	M	H	L	L	M	H
14	M	M	H	L	M	H	L
15	M	M	H	L	H	L	M
16	M	H	L	M	L	M	H
17	M	H	L	M	M	H	L
18	M	H	L	M	H	L	M
19	H	L	H	M	L	H	M
20	H	L	H	M	M	L	H
21	H	L	H	M	H	M	L
22	H	M	L	H	L	H	M
23	H	M	L	H	M	L	H
24	H	M	L	H	H	M	L
25	H	H	M	L	L	H	M
26	H	H	M	L	M	L	H
27	H	H	M	L	H	M	L

L - Low, M - Medium, H - High

factorial experiment with seven factors each at three levels would require $3^7 = 2187$ experiments to be conducted, which was time consuming and costly for the organization (Montgomery 1991). Hence, it was decided to conduct a fractional factorial experiment with the help of orthogonal arrays. The orthogonal array L_{27} (3^{13}) was selected for conducting the experiment. As per the orthogonal array L_{27} (3^{13}), the master plan of the experiment was prepared and is presented in Table 3. Each of the experiments given in Table 3 was conducted two times and data were recorded. These data were analysed by Taguchi's signal to noise (S/N) ratio method (Phadke 1989). Since maximum V_{oc} is preferred in a process, the S/N ratio of larger-the-better type was selected for analysis. The formula for calculation of S/N ratio of larger-the-better type is

$$-10^* \log \left(\frac{\Sigma(1/Y^2)}{n} \right),$$

where Y is the response measured during experimentation (Taguchi 1986). The S/N ratio values were calculated for each of the nine experimental combinations. These S/N ratio values were subjected to further analysis to identify the optimum factor level combination.

From the main effect plot (Fig. 5) of S/N ratios, the best levels for factors were identified as the level corresponding to the highest value of S/N ratio (Phadke 1989). The optimum combination thus arrived is given in Table 4. The optimum factor level combination was implemented in the process and results were observed. The process capability analysis was performed by using Minitab software and the output is presented in Fig. 6. From Fig. 6, the observed ppm was found and the corresponding sigma level was calculated and is 4.01. The average value of V_{oc} was improved from 614 to 617 mV and the standard deviation reduced from 0.0061 to 0.0041. The

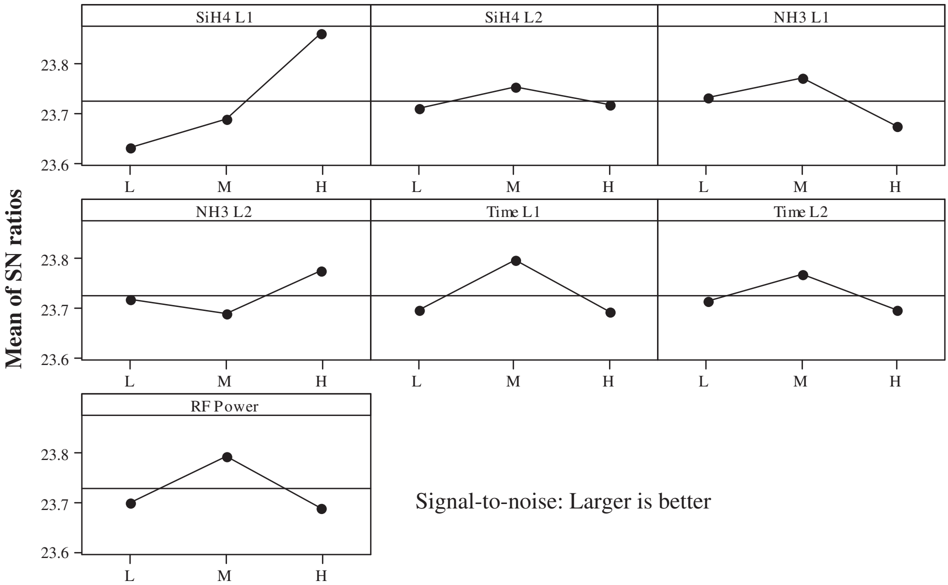

Figure 5. Main effects plot for efficiency.

Table 4. Optimum factor level combination.

S. No.	Factors	Optimum level
1	Silane flow layer 1	High
2	Silane flow layer 2	Medium
3	Ammonia flow layer 1	Medium
4	Ammonia flow layer 2	High
5	Time for layer 1	Medium
6	Time for layer 2	Medium
7	RF power	Medium

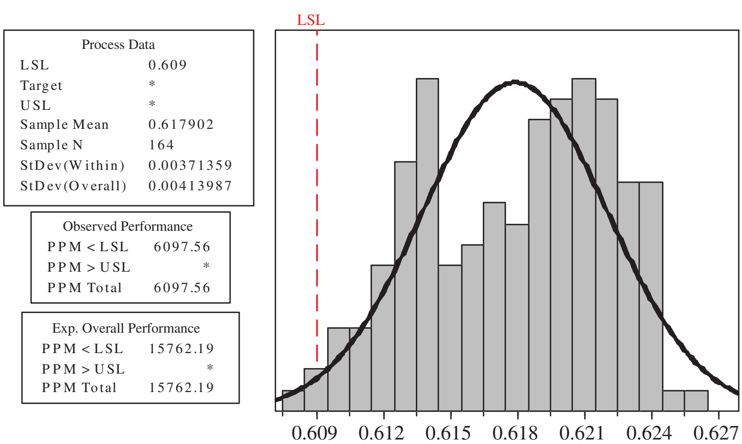

Figure 6. Process capability analysis on V_{oc} after improvement.

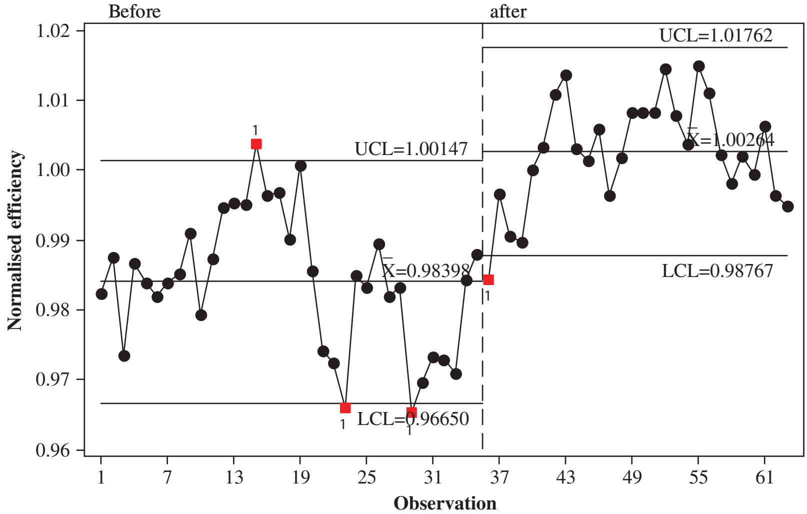

Figure 7. Run chart for normalized efficiency before and after the optimized process.

sigma value was improved from 2.67 to 4.01, clearly indicating significant improvement in process performance.

The objective of the control phase is to ensure sustainability of the achieved results. Due to many organizational reasons, maintaining the results is extremely difficult (Gijo 2005). A system for standardization and continuous monitoring of the results are to be established in the control phase. The implemented solutions were standardized by incorporating it in process procedures and work instructions. This ensures that every one follows the improved process parameters and data from the process was recorded and reviewed. Results before and after the project were compared by using the individual chart (Fig. 7). It is evident from Fig. 7 that the efficiency improved significantly.

5. Summary/conclusion

Silicon nitride films have been deposited by the direct PECVD process on multicrystalline silicon solar cells. A set of process gas flow rates provides excellent surface passivation and optimum anti-reflective properties from a dual layer silicon nitride film. Six Sigma DMAIC methodology has been successfully applied for optimizing the particular recipe of the PECVD process to enhance the efficiency of the multicrystalline silicon wafer. The different phases of the approach were systematically applied to the process and the sigma level of the V_{oc} improved from 2.96 to 4.01. As a result of the optimized process, the efficiency level of the solar cell improved significantly, which has been observed consistently. This study and the electrical results reveal the importance of the PECVD process in the conventional PV manufacturing processes.

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