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An effective way to analyse the performance limiting parameters of poly-crystalline silicon solar cell fabricated in the production line

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Abstract

This article focuses on the identification of key features that are responsible for the discrepancies in the performance of silicon solar cells fabricated on multicrystalline silicon under the identical conditions. In an experimental approach, direct current (DC) measurement coupled with alternating current (AC) characterisation technique has been employed. The scanning electron microscope analysis reveals an average grain size of few micrometres for all the solar cells and the top surface of least efficient solar cell contains the impurity precipitates with deep cone shaped holes or pits. The DC measurement reveals that the photocurrent density loss follows an exponential behaviour with respect to the current–voltage characteristics for all the solar cells. The analysis of $-dV/dJ$ versus $(J_{SC} - J)^{-1}$ plot and the variation of ideality factor with junction voltage demonstrate that the higher resistive and recombination losses dominate the performance of least efficient solar cell. Impedance Spectroscopy (IS) technique is used to quantify and decouple the various photovoltaic parameters associated with the different physical processes. A lower value of shunt resistance and minority carrier lifetime along with the higher value of series resistance contribute to the higher resistive loss and surface recombination. The experimental results along with the analytical model provide an insight into the loss mechanisms and the use of a simple tool that can be integrated with the conventional photovoltaic testing.

Keywords: Poly-crystalline silicon solar cell; Recombination kinetics; Minority carrier lifetime; Impedance spectroscopy

1. Introduction

In the quest of low cost and high efficiency solar energy conversion device, multi-crystalline silicon (mc-Si) solar cell demonstrates its ability to fulfil this requirement where power conversion efficiency of >17% is realised with a total worldwide installation of 70% till 2014 (Lee et al., 2011). The performance of a solar cell strongly depends upon the electrical properties of Si wafer, back surface field (BSF), surface passivation and current collector grid, and optical properties of surface texturing, anti-reflection coating (ARC), etc. Green, 1982. Moreover, the different processes taking place at n^+–p junction, p–p^+ junction

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(i.e. injection, separation and diffusion of charge carriers), and charge transport and recombination in the bulk of semiconductor also influence the performance of solar cell to a great extent (Green, 1982).

The investigations on the mc-Si solar cell technology have introduced a new and novel design of ARC, BSF, current collector, etc. Ye et al. (2014) have reported a power conversion efficiency of 18.45% for nanoscale pseudo-pyramid textured multi-crystalline silicon solar cell fabricated by metal-catalysed chemical etching on an industrial production line. A substantially improved efficiency of 19.8% for a mc-Si solar cell is achieved by enshrouding cell surfaces in thermally grown oxide to reduce their detrimental electronic activity (Zhao et al., 1998). The feasibility of new developments have been characterised through the performance indicating parameters of solar cell namely; open circuit voltage (V_{OC}), short circuit current density (J_{SC}), ideality factor (m), fill factor (FF), power conversion efficiency (η), and series and shunt resistance (R_S and R_{SH}). In the silicon solar cell the features like BSF, selective contacts, surface and interfacial phenomenon became standard in the last few years (Green, 1982; Yin et al., 2013). The present electrical characterisation technique integrated in the conventional photovoltaic (PV) testing cannot resolve the electrical response of these features. Impedance spectroscopy (IS) has a potential to provide an insight into the energetics and kinetics of these features in a new solar cell (Yadav et al., 2014). IS is a small amplitude perturbation, frequency domain technique that resolves the interfacial and bulk properties of a solar cell in terms of its resistive and capacitive response under the steady state condition (Santiago et al., 2007; Yadav et al., 2015; Kim et al., 2013). In recent past this technique has been used to evaluate silicon wafers (Kumar et al., 2010) and solar cells (Kumar et al., 2009) also.

In this article, differences in the performance of silicon solar cells have been investigated by DC and AC characterisation techniques. The study is mainly focused on (i) elucidating the recombination and resistive losses in the fabricated solar cells, (ii) decoupling the various photovoltaic parameters associated with different physical processes in terms of resistive and capacitive elements, and (iii) analysis of relaxation time associated with the solar cells. The observed higher value of ideality factor and lower value of R_{SH} signify the high density of electrically active defect states at grain boundaries leading to the tunnelling assisted recombination or charge-coupled assisted recombination. Moreover, the experimental results along with the analytical model provide an insight into the loss mechanism and the use of a simple tool that can be integrated with the conventional photovoltaic testing.

2. Experimental

The Si solar cells were fabricated by using a $156 \times 156\ \text{mm}^2$ p-type multicrystalline silicon (mc-Si) wafer having a thickness of ~180 μm after damage removal (~8–10 μm layer from both sides) and surface texturing (formation of low reflectivity surface). However, during these processes, the etching of grains of different orientations and the grain boundaries may be different and non-uniform. The wafers were taken from the same ingot but from different portions along the growth direction. In a wafer, the grain size and impurity distributions change along the growth direction in an ingot. The p–n junction was formed by phosphorous diffusion at 850 °C for 60 min. The phosphor-silicate glass (PSG) was removed by HF etching followed by plasma enhanced chemical vapour deposition (PECVD) of ≈80 nm SiN_x at 400 °C which acts as an anti-reflection coating (ARC). Further, front and rear contacts were formed by standard silver and aluminium screen printing followed by co-firing and LASER edge-isolation. Three representative cells were selected for the present analysis based on their efficiencies of 17.56%, 16.8% and 16% which will be further referred as Cell 1, Cell 2 and Cell 3, respectively.

The fabricated silicon solar cells were tested using field emission scanning electron microscope (FESEM), direct current (DC) and alternating current (AC) characterisation techniques. The FESEM images were collected using Carl Zeiss Scanning Electron Microscope with an operating voltage range of 1–20 kV under ultra-high vacuum conditions. The current–voltage (J–V) characterisations were done using Photoemission Tec SS80AAA solar simulator equipped with 1.5AM-G filter and U2722A Agilent source measuring unit (SMU). AC measurements were performed using a three electrode potentiostat CHI 660D equipped with a frequency response analyser. The working electrode was connected to the positive terminal of Si solar cell (i.e. on back side) whereas reference and counter electrode were shorted and connected to the negative front terminal of Si solar cell. IS measurements were performed in the DC bias range of −0.5 to 0.65 V with an AC perturbation signal of 5 mV in the frequency range of 0.1 Hz to100 kHz. During all the electrical measurements, Si solar cells were mounted over the heat sink to maintain a constant temperature.

3. Results and discussion

3.1. Morphological and J–V characterisation

Fig. 1 shows the top view and cross sectional FESEM images of Cell 1 and Cell 3. The deep cone shaped holes or pits and impurity precipitates on the top surface of cells are shown by the marked regions in Fig. 1A and C respectively. The source for holes or pits may be a high concentration of metallic impurities distributed randomly in Si wafer which dissolves under acidic or basic texturization process. The difference in concentrations of metallic impurities in the same ingot can be attributed to the different diffusivity of metallic ions or atoms at high temperature during ingot formation.

The top view of both the solar cells shows an inhomogeneously distributed oval shape pits with an average grain