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Grouping by bulk resistivity of production-line mono-crystalline silicon wafers and its influence on the manufacturing of solar cells modules

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Abstract

Weak light performance of crystalline silicon solar module presents a clear dependence on the type of cell used, mainly wafer resistivity and shunt resistance. This paper shows that a proper wafer and cell classification can provide a further optimization opportunity. This means a well-controlled product fabrication and production line yield improvement without an additional cost. For these reasons a resistivity boron-doped Czochralski silicon (Cz–Si) wafer classification has been implemented as the first stage of a photovoltaic monocrystalline silicon solar cell production line which allows to process solar device batches with similar raw material properties. This new production stage leads to a narrower solar cell efficiency distribution and a tailored power photovoltaic module fabrication. After that, solar cell devices have been sorted by shunt resistance criterion. Their behaviors under weak light conditions have been carefully studied at cell and module levels. Finally, one and two diode models have been used to justify the obtained results.

Keywords: Solar cells; PV modules; Silicon wafer resistivity

1. Introduction

Nowadays, the industrial photovoltaic (hereafter named as PV) solar cell production is mainly based on boron doped crystalline silicon (c-Si) which includes single-crystal as well as multicrystalline silicon. Although both materials follow the same production sequence (alkaline texture process, P-diffusion, silicon nitride antireflective coating, metal contact firing and PV solar cell sorting), they present important wafer cost differences (multicrystalline wafers are the cheapest ones) and final power output variability (monocrystalline silicon PV devices featuring the highest one). Focused on B-doped Czochralski (Cz–Si) technology, two main issues have to be mentioned: their initial degradation named as light induced degradation (LID) and their efficiency behavior under weak light operation conditions. It is well known that the initial degradation suffered by this technology results in a low minority carrier lifetime and it is related with boron–oxygen active complex formation (Schieferdecker et al., 2011; Schmidt and Cuevas, 1999; Macdonald et al., 2004; Schmidt et al., 1997, 2004). This temporal degradation is not developed during the cell production and it is fully reversible by annealing above ≈200 °C. Regarding PV module behavior under weak light conditions, the efficiency drop is related with raw material properties and the PV cell parasitic

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resistances. Currently these two issues can be measured at solar device production facilities.

In a production line, the current–voltage (I–V) curve of the PV device is provided by the solar cell testers (López-Escalante et al., 2016). These instruments are a key in-line characterization tool as they can measure the most usual parameters under illumination and dark conditions: short circuit current density (J_{sc}), open circuit voltage (U_{oc}), maximum power point (P_{mp}), current density and voltage for this point (J_{mp} and U_{mp}), fill factor (FF), series (R_s) and the shunt resistance (R_{sh}). Regarding R_{sh} and R_s, they are parasitic parameters, which lead to a reduction of the solar cell efficiency (Radziemska, 2005). In a n^+p or n^+pp^+ silicon solar cell, R_s is mainly the sum of three factors: the front and back surface contact resistance, the bulk resistances and the n^+ top diffused layer. R_{sh} represents a parallel high-conductivity path across the PV cell p–n junction and it is the main parameter involved in the cell efficiency decrease (Wolf and Rauschenbach, 1963; McIntosh and Honsberg, 2000). Industrial produced Cz–Si solar cells with screen printed contacts use to have a moderate R_{sh} (Breitenstein et al., 2004).

The solar cell I–V curve can be presented either by a single diode or by a two diode models. The single diode model is, however, the most popular one (Cuce et al., 2013). The two-diode model is frequently used under dark conditions (Bouzidi et al., 2007).

This work is focused on two main objectives: the first one is to determine if initial wafer resistivity segregation can lead to a improvement in production yield without additional cost or production time delay. For this goal, bulk resistivity ranges have been defined and they have been implemented in an automatic resistivity tester. This industrial equipment has been placed previous to the wet line stage and the operator processed each group of cells separately basing on their resistivity. Regarding measured I–V curves, a careful parameter analysis has been carried out and also a relation between the efficiency distribution and their respective resistivity groups has been established. The second aim of this work is to determine the bulk resistivity together with the R_{sh} influence in the final output power of the PV device (both cell and modules). For the latter case, a second R_{sh} classification has been carried out and PV solar cell and module behavior under weak light conditions have been studied per wafer resistivity and R_{sh} group. Finally, results have been justified by Kahn's procedure (Khan et al., 2010) which is based on one diode model. Additionally, main parameter differences per group have been determined by a second diode model.

2. Basic equations of the device

The steady state I–V characteristics of a p–n junction silicon solar cell are often described based on a one and/or two diode model. PV cell I–V curve parameters are controlled by these models at any given illumination level and their numerical values can be determined. These parameters are: J_{sc}, U_{oc}, J_{mp}, U_{mp}, P_{mp}, FF, R_s and R_{sh}. The one-diode model (Eq. (1)) is the simplest way to describe the I–V curve characteristic of the silicon solar cell p–n junction (Khan et al., 2010). In (1), I_0 is the reverse saturation current of the cell, q is electron charge, k is Boltzmann constant, T is the operating temperature of the cell (expressed in K), R_{sh} is the shunt resistance, R_s is the series resistance, n is the diode ideality factor and I_{ph} is the light generated current. Different methods have been developed to apply the former equation (Cuce et al., 2013; Khan et al., 2010; De Soto et al., 2006; Orioli and Di Gangi, 2013; Boyd et al., 2011; Mermoud and Lejeune, 2010). In this work, the method described by Khan et al. (2010) has been selected because the procedure can be carried out with the equipment located at our facilities. These methods divide a very wide intensity range into a number of smaller intensity ranges, whereby the cell parameters remain constant. The four cell parameter values (R_{sh}, R_s, n and I_0) are analytically determined from the I–V curve slope variations for both short and open circuits in all the smaller intensity ranges. In this work, silicon solar cells I–V characteristics have been registered at four different irradiance levels. Then, the described method by Khan has been used to determine three of the four parameters: I_0, n and R_s. The value of R_{sh} is not determined because it is given by the solar cell tester.

$$I = I_0\left(e^{\frac{qV_j}{nkT}} - 1\right) + \frac{V_j}{R_{sh}} - I_{ph} \tag{1}$$

$$V_j = V - IR_s \tag{2}$$

A negligible recombination in the space-region is assumed by the one diode model expression. However, this is not true in practice. Defects in the semiconductor can result in traps, which allow the minority charge carrier recombination in the space-charge region. Thus, the one diode equation is modified to incorporate this recombination current given by:

$$I = I_{01}\left(e^{\frac{qV_j}{n_1kT}} - 1\right) + I_{02}\left(e^{\frac{qV_j}{n_2kT}} - 1\right) + \frac{V_j}{R_{sh}} - I_{ph} \tag{3}$$

$$V_j = V - IR_s$$

In this equation, I_{01} and I_{02} represent the first and second diode saturation currents; R_s and R_{sh} are the series and shunt resistances, respectively; n_1 and n_2 denote the first and second diode ideality factors, respectively; q is the electron charge, k is the Boltzmann constant, T is the temperature and I_{ph} is again the light-generated current.

Dark current–voltage (dark I–V) measurements are commonly used to analyze solar cells electrical characteristics. This provides an effective way to determine fundamental performance parameters. Although the dark I–V measurement procedure does not provide information regarding the I_{sc} (non-illumination conditions imply I_{ph} equal to zero because of the absence of the light, making the current generation negligible), it is more sensitive than light I–V measurements in determining the other parame-