Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 130 (2016) 184–192
SOLAR ENERGY
www.elsevier.com/locate/solener

Comprehensive analysis and modeling of cell to module (CTM) conversion loss during c-Si Solar Photovoltaic (SPV) module manufacturing

J.N. Roy

School of Energy Science & Engineering & Advance Technology Development Centre, Indian Institute of Technology, Kharagpur 721302, India

Received 1 October 2015; received in revised form 12 January 2016; accepted 11 February 2016

Communicated by: Associate Editor Mario A. Medina

Abstract

Cell to module (CTM) conversion loss, during Solar Photovoltaic (SPV) module manufacturing, in terms of wattage losses, at critical process steps Tabbing and Stringing (T&S) and Lamination have been analyzed and a comprehensive electrical and optical model presented. The relation between efficiency of the starting cells and CTM loss has been established. The optimization criteria of the T&S process, in terms of ribbon dimensions and the cell parameters, has also been described. CTM conversion loss/gain for lamination process has been modeled using refractive index and thicknesses of various thin film layers on cell with and without lamination. A guideline for selecting these parameters for obtaining optimized efficiency for laminated cells has been presented. The effect of added electrical resistance due to junction box and change of optical property due to anti reflection coating (ARC) on cover glass have also been presented in brief for completeness. Indoor as well as outdoor test data have been used for modules with ARC on cover glass. During outdoor test, measurements have been carried out with varying intensity and angle of incident of the light. T&S and lamination models have been validated by experiments conducted on single cell coupons. The power loss due to junction box and power gain due to ARC on cover glass has been done on full 60 cell modules. The models described here have been successfully used by the author for minimizing CTM conversion loss for two types of cells with known cell process parameters.

Keywords: Photovoltaic; Conversion loss; Optical modeling; Lamination

1. Introduction

Crystalline Silicon (c-Si) Solar Photovoltaic (SPV) module manufacturing takes solar cells through a number of process steps. The additional electrical and optical effects introduced during the manufacturing of SPV modules results power loss (or sometime gain) as compared to that of solar cells used to make the module. The difference between input power and the output power is known as cell to module (CTM) conversion loss which is to be minimized. It is therefore important to understand and model the causes of this loss so that process, materials and design can be accordingly optimized during manufacturing.

Improvement of the efficiency of solar cell is to get more power output from same area is a subject of current research. c-Si solar cell technology has made significant progress in last decade. The efficiency improvement is mainly achieved by tackling electrical resistance, External Quantum Efficiency (EQE) Park et al., 2013; Macdonald et al., 2004 and Internal Quantum Efficiency (IQE) Yang

E-mail address: jatinroy2000@gmail.com

http://dx.doi.org/10.1016/j.solener.2016.02.020
0038-092X/

et al., 2008; Dimassi et al., 2011. The cell to module (CTM) conversion typically results in loss, which is determined by module manufacturing technology (material and process), and more importantly the type and efficiency of the input cells. It has been seen and described later in this paper that the CTM loss is generally more for high efficiency cells. Although not common, it is possible to achieve a small conversion gain for module made with low efficiency cells. The power output changes due to additional electrical and optical effects introduced by various stages of module manufacturing process, such as Tabbing–Stringing–Bussing (Jung et al., 2014), Lamination (Mickiewitcz et al., 2012) and Junction Box (European committee for electrotechnical standardization, 2012). Reduction of CTM loss occurring due to module manufacturing process has been an important subject. Several innovative techniques have been tried. Enhancement of light capture by reflection (Su et al., 2011; Chung et al., 2012), ARC on Glass (Bunea et al., 2010; Wohlgemuth et al., 2015), conductive adhesive for tabbing and stringing (Hsieh et al., 2010; Zemen et al., 2013), lamination with silicone gel (Poulek et al., 2012) are some of the notable innovations. Several authors reported models of CTM loss attributed to different materials and processes; such as encapsulation (Grunow and Krauter, 2006), resistance introduced due to spot soldering (caballero et al., 2006), mismatch between cells (Louis and Bucciarelli, 1979; Kaushika and Rai, 2007; Webber and Riley, 2013), overall reflection (Scheydecker et al., 1994; Koomen et al., 1996), textured cover glass (Campbell, 1990; Cardona et al., 2008), etc. The effect of temperature on optical loss has also been reported (Lu and Yao, 2007; Krauter and Hanitsh, 1996). More basic models (El-Basit Wafaa et al., 2013) relates illumination and temperature effects to the parameters such as series, shunt resistance and power output.

The effect of cell type and efficiency are not addressed by these models. It has been seen by the author that the overall CTM conversion loss has strong relation with the input cell types. In this work, eight different types of cells have been used to develop a comprehensive model to address electrical as well as optical power loss/gain. The cells used are from different manufacturers with varying efficiency, mono and multi crystalline and 2 and 3 bus bars. A guideline for optimum material and process parameters depending on cell types has been presented. The effect of the ARC on cover glass has also been added in this analysis and modeling. It may be noted that the basic process flow and steps used in a SPV module manufacturing have not been disturbed to make this model practical and readily usable. As per the knowledge of the author such comprehensive model and analysis are not available in the literature.

2. Process flow and experimental details

A certified module manufacturing line (Roy et al., 2010) has been used to collect the experimental data. The layup sequence is depicted in Fig. 1. Experimental data has been collected by making single cell coupons. AAA class solar cell tester from SPIRE Corporation (Spi-Cell Tester™) www.spiresolar.com has been used to measure powers at various stages of manufacturing; bare cells, tabbing–stinging, bussing and lamination. The power changes due to junction box and ARC on cover glass have been determined by making full size modules of 60 cells (Roy et al., 2010). Experimental data have been collected from single cell coupons made using eight different types of 156 mm × 156 mm size cells. The cell description, without disclosing the manufacturer's name, has been given in Table 1. The cell types chosen are combination of comparatively low (Type-4 and Type-5), moderate (Type-2 and Type-3, Type-6) and high (Type-1, Type-7 and Type-8) efficiency.

Fig. 2 shows the configuration of the coupon before and after tabbing–stringing (T&S) and bussing. The same cells are then tabbed–stringed–bussed and measured again. The cells and cell coupons have been tested on a Cell-tester pre and post tabbing–stringing–bussing. Standard tabbing ribbon of 2.4 mm × 0.13 mm for 2BB cells and 1.7 mm × 0.13 mm for 3BB cells was used. For clarity, the tabbing ribbon for the back bus bar in Fig. 2 is shown a bit wider. The results reported here is the average of five cell coupons of each cell type. L_{TB} of 150 mm and L_{CB} of 20 mm (see Fig. 2b) have been used for making cell coupons. L_{BB} is the property of the cells. The configuration of the 3BB cell coupons is similar.

The lamination of the cell coupons was done, keeping the same configuration of Fig. 1, using a Jinchen laminator (www.jinchensolar.com). Lamination temperature of 145 °C and total cycle time of 18 min have been used. It is not

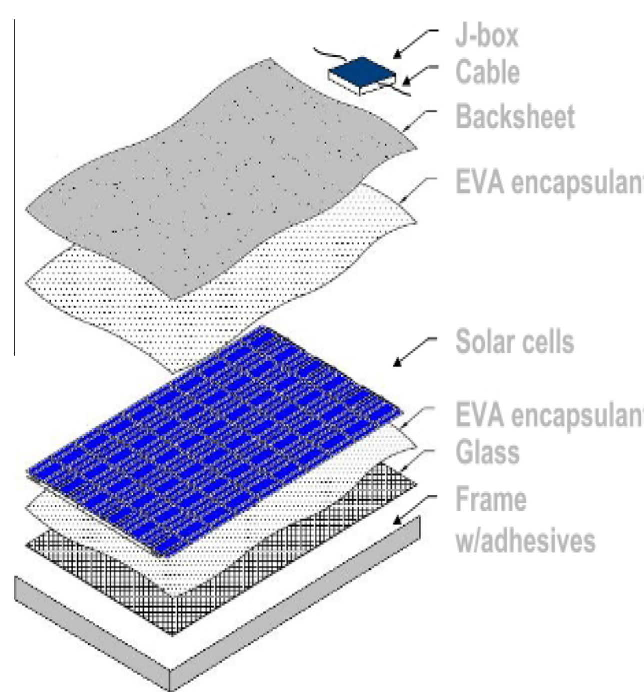

Fig. 1. Typical lay-up sequence of a Solar Photovoltaic (SPV) module manufacturing.