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A numerical model for soldering process in silicon solar cells

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ABSTRACT

Solar or Photovoltaic (PV) cells are utilized to convert solar energy into electricity through the photovoltaic effect. Although, Silicon solar cell is one of the most prevalent type of solar cells; manufacturing of this type of solar cells especially soldering copper electrodes to the silicon wafer is very challenging. If the soldering parameters are not selected properly, small cracks will be created in silicon layer, and finally, fracture of the solar cell will happen. The goal of the present study is to develop, for the first time, a finite element model to simulate the soldering process in the fabrication of silicon solar cell in which the soldering system is passing over the solar cell to connect the copper electrode to the silicon wafer. The temperature and thermomechanical stress distributions induced in different layers of the cell are extracted. The effects of several parameters such as soldering power, soldering speed, and the thickness of silicon wafer on the temperature and stress distributions are probed. The results show that the silicon layer is the most critical layer in a silicon solar cell during the soldering process which is susceptible to high thermomechanical stresses. It is shown that increasing the soldering system power and decreasing the soldering system speed lead to increase of thermomechanical stresses induced in the silicon wafer. In addition, using thicker silicon wafer can decrease the thermomechanical stresses generated in this layer.

1. Introduction

A solar cell, or photovoltaic cell, is an electrical device which can generate electricity by the photovoltaic effect (Green, 1982; Uchino et al., 1982; Azzouzi and Chegaar, 2011). The photovoltaic effect is a physical and chemical phenomenon which results in converting the energy of light directly into electricity (Hersch and Zweibel, 1982). There are different types of photovoltaic modules including crystalline solar cells, thin film technologies (CIGS, CIS, CdTe, a-Si), and organic cells (Fraas, 2014; O'regan and Grfitzeli, 1991). Although producing crystalline silicon wafer-based photovoltaic modules are more expensive than thin film solar panels or organic modules (Haberlin and Eppel, 2012; Chaturvedi et al., 2013); they extensively are used all over the world due to their ability to achieve the highest conversion efficiencies (Goetzberger et al., 1998).

A typical crystalline solar cell consists of various material layers with different properties (Goetzberger et al., 1998). These sandwiched structure solar cells, based on the specific pattern, are connected to each other by copper or silver (Ag) wires. The soldering of the wires to the solar cells results in generating significant thermomechanical stresses in different layers due to the diversity of thermal expansion of different components. This thermomechanical stress during the soldering step can lead to small cracks in the solar cells (Lai et al., 2014; Breitenstein et al., 2004; Kaule et al., 2014; Eitner et al., 2010; Schulte-Huxel et al., 2012). These cracks may grow when the solar panel is subjected to different temperatures of day and night or summer and winter.

On the other hand, the need to reduce PV manufacturing costs (Goodrich et al., 2011) and the shortage of polysilicon feedstock are driving a reduction in wafer and cell thicknesses. During last few years, the thickness of the wafers has decreased from about 300 to 150 μm (O'regan and Grfitzeli, 1991; Chen et al., 2008); therefore, they become more susceptible to mechanical damages. As wafer becomes thinner, more consideration should be given to the soldering process during solar cell fabrication.

Some studies have been conducted to analyze the stresses and bow induced in the solar cell due to the soldering process (Möller et al., 2005; Yoon et al., 2014; Hilali et al., 2007; Bähr et al., 2005). They have recognized several factors having significant influences on the thermomechanical stresses generated in the silicon layer. Chen et al. (2008) studied the effect of soldering temperature, the thickness of the silicon wafer and the thickness

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of the copper wire on the bow and the residual stresses induced in the silicon layer resulting from the soldering process. The results indicated that increasing the soldering temperature and decreasing the silicon wafer thickness will result in increasing the bow and residual stresses induced in the solar cell. Wiese et al. (2008) investigated the influence of silicon thickness and the mechanical properties of the copper wire on the bow generated in silicon layer during soldering wire to the silicon wafer. Coulter et al. (2009) showed that increasing the thickness of silicon wafer will result in decreasing the bow of the silicon layer while increasing the thickness of the Al back sheet layer bring about increasing the bow of the silicon layer during the soldering process. Wiese et al. (2010) probed the effect of Young's Modulus, yield stress, and the dimensions of the copper wire on the principal stresses induced in silicon layer during the fabrication process. The results revealed that increasing the Young's Modulus and the yield stress create higher stresses in the silicon wafer. Lai et al. (2014) showed that the maximum stress generated in the silicon layer during the soldering process takes place at the end point of the connection line of the wire to the silicon layer. Moreover, they inspected the effect of the silicon wafer thickness and copper wire dimensions on the maximum stresses exist in the silicon layer during solar cell fabrication. Yixian and Tay (2012) investigated the maximum stresses induced in the silicon wafer, the glass layer, and the aluminum back sheet layer during the fabrication process and compared them with each other. In another paper, Maturi et al. (2014) examined the thermomechanical stresses generated in the silicon solar cell during its operation under different temperatures. The results lead to the conclusion that among all the components making a solar cell, too many attentions should be given to the silicon layer due to having the maximum stress during solar cell fabrication and operation, in conjunction with its brittleness.

Most of the studies above are mainly focused on simulating the cooling stage after the soldering process. Their results provide a broad look at the stress concentration in a solar cell after soldering process in which the cell temperature cools down to ambient temperature. However, according to our literature review, the temperature distributions generated in the different layers during the soldering process and their associated thermomechanical stresses have not been discussed yet. Moreover, the temperature distribution in different layers of the solar cell and the temperature of whole the silicon layer has been assumed to be uniform in the all related studies. However, while the soldering system is passing through the silicon layer to make a connection between copper wires and the silicon wafer, a region called heat-affected zone (HAZ) is generated. The temperature of HAZ is higher than the temperature of other regions of the solar cell. Consequently, a stress distribution in different layers of the solar cell during the soldering process is generated. Also, after removing soldering system (during the cooling process) the temperature of the whole solar cell is not uniform.

In the present study, for the first time, a finite element model is developed to simulate the soldering process while the soldering system is passing over the solar cell. The temperature distribution and the thermomechanical stresses induced in the different layers of the solar cell during the soldering process and after finishing the soldering in which the solar cell cools down to ambient temperature are probed. Moreover, the effective parameters on temperature and stress distributions are described.

2. Finite element model

The main goal of the present work is to simulate the effect of soldering process of the copper wire into the solar cell on the thermo-mechanical stresses induced in the silicon solar cell during this process. In fact, the soldering process affects the cell status by its two effects: (1) heat generation and consequent thermal gradient in the components (2) joining the copper ribbon to silicon wafer. Actually, the soldering process is simulated by incorporating and simulating these two effects in the model. Therefore, to simplify the model, simulation of the solder melting is not incorporated in the model.

The modeled solar cell consists of several layers including aluminum (Al) back sheet layer, silicon wafer and the wire composed of a layer of copper sandwiched in two layers of solder. Fig. 1 shows the solar cell structure used for modeling in the ABAQUS (Dassault Systèmes) commercial finite element package to simulate the mechanical behavior of a solar cell under soldering process. The type of the solar cell simulated in this study is a monocrystalline silicon solar cell with the dimensions of 156 mm by 156 mm which is the same as the dimension of Al sheet layer. The copper ribbons providing the series connections of the cells have the geometry of 2 mm by 156 mm. The thicknesses of the silicon wafer, Al layer, the copper and the solder ribbons are assumed to be 200, 40, 80, and 40 μm respectively. Since the size in the thickness direction is much less than the planar dimensions, shell elements are adopted in the finite element analysis (FEA) model.

In the present model, the silicon wafer is on the top and the Al layer is placed on the bottom of silicon layer. Copper wires are attached to the solar cell, on the silicon wafer to connect several solar cells to each other. Also, to cut down the computational cost and efforts, only one-half of the cell is modeled due to the symmetry of the cell with respect to the X direction.

2.1. Physical and mechanical properties

It is assumed that the aluminum, the copper and the solder shows elastic and plastic behaviors. Therefore, the elastic-perfectly plastic model of the material is adopted for the aluminum, the copper, and the solder. Since silicon is a brittle material, only the elastic properties are defined for this layer. The mechanical properties of different layer materials are shown in Table 1.

Linear thermal expansion coefficient describes the temperature effect. There is thermal conduction in each layer of the solar cell and also between different layers during the soldering process which should be considered. The density and specific heat are required for probing the temperature distribution when the soldering system is passing through the solar cell and also during the cooling down process. The physical properties of different layer materials are shown in Table 1.

2.2. Mechanical loading

The cells are usually held during the soldering process either manually or using some specific holders to avoid any displacement. Therefore, a boundary condition of zero displacement in the Z direction is applied to the back surface of the solar cell to avoid from its rigid displacement. Also, one point of the solar cell is set not to have any movement in X and Y directions too. The copper layer is assumed to be not tied to the silicon wafer before soldering process. By passing soldering system over the copper wire, it is being connected to the silicon wafer.

During the soldering process, a soldering system with specified characteristics such as thermal power and speed is passing over the copper ribbon to connect it to the solar cell. The heat is transferred from the soldering tool to the copper ribbon, and then, it will be transferred from the copper ribbon to the silicon wafer directly through conduction. In addition, heat transfer along the copper ribbon via conduction is also considered in the model. In the model, it is assumed that there is no thermal resistance between copper rib-