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A comprehensive study of intermetallic compounds in solar cell interconnections and their growth kinetics

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Abstract

Intermetallic compounds (IMC) in soldered interconnections influence the reliability of PV modules. Thus, the microstructure of solar cell interconnections and the growth of IMCs are to be investigated in this paper. Sn60Pb40 and Sn41Bi57Ag2 are chosen as alloy coatings of copper interconnectors and semi-automatically soldered to screen-printed front Ag-busbars of industrial mono-crystalline solar cells. The microstructure of the solder bonds is characterized with metallographic cross sections and confocal laser microscopy, as well as scanning electron microscopy and electron dispersive x-ray spectroscopy. The cross section samples are isothermally aged between 85 °C to 150 °C and for 15 hour to 155 hour to obtain the kinetic parameters of a diffusion-based growth model of the IMCs. The model is used to estimate the IMC thickness after 3000 h at 85 °C, and after 600 thermal cycles as well as after 25 years in the outdoor location Freiburg, Germany. It is found that extensive microstructural changes take place within the solder bonds during thermal aging. Grain coarsening within the solder matrix, in particular for Sn41Bi57Ag2 solders, is observed, which can lead to an entire Sn depletion of the solder matrix. Moreover, non-uniform Sn penetration and IMC growth at cavities and lead-glass particles of the busbar are observed for both solders, which is discussed in terms of its effect on metallization adhesion. Eventually, simulating the IMC growth for 3000 h at 85 °C forecasts a 3.7 μm thick Ag_3Sn IMC at the busbar for the Sn41Bi57Ag2 solder compared to 2.6 μm for Sn60Pb40. The prognosis of the IMC thickness after 25 years in Freiburg yields an Ag_3Sn thickness of 1.3 μm for Sn41Bi57Ag2.

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1. Introduction

Photovoltaic modules are designed to survive 25 to 30 years of outdoor operation, and improving their lifetime vastly decreases the levelized costs of electricity of photovoltaic systems [1]. Against this background, the quality of series interconnection of crystalline silicon solar cells into strings, which is part of the PV module integration

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process, has a direct impact on the reliability of the PV module. Hence, understanding of solder bonds and their failure mechanisms can improve the reliability of PV modules.

The existence and growth of intermetallic compounds (IMC) within solder bonds influences the lifetime of the interconnections. After the joining process, IMCs exist within the solder matrix and, in most cases, at the interfaces to the solar cell metallization and the copper core of the ribbon as uniform and thin layers. They are an indication for a proper mechanical and electrical bond [2]. However, IMCs grow due to solid state aging at elevated temperatures or even storage at room temperature. Owing to their brittleness and the large mismatch of coefficients of thermal expansion (CTE) of the involved materials in the joint ($CTE_{Si} \approx 2.6 \times 10^{-6}\,K^{-1}$ and $CTE_{Cu} \approx 17 \times 10^{-6}\,K^{-1}$) cracks can easily be induced and propagated when the bond is exposed to thermal cycles or mechanical load [3, 4, 5, 6, 7].

In this paper we describe the microstructural changes of PV module solder bonds observed during thermal aging. Interconnector ribbons with a standard lead-based Sn60Pb40 solder coating along with a low melting point solder Sn41Bi57Ag2, which is under consideration for the interconnection of temperature sensitive high-efficiency solar cells, is used in the experimental investigation [8].

The growth kinetics of IMCs in PV module solder bonds is modeled. The model's Arrhenius parameters are obtained by systematic aging studies at varying temperatures. The model is then used to simulate the IMC growth during accelerated aging tests and during outdoor operation of a PV module in the location Freiburg, Germany.

The work presented here extends and deepens previous investigations of IMCs in solar cell interconnections [9, 10, 11]. Particularly, a direct comparison of the bismuth-based solder coating to standard lead-based solder and modeling of the phase growth with non-isothermal temperature profiles are new aspects presented in this work.

Nomenclature

CTE	coefficient of thermal expansion
$D(T)$	Diffusion coefficient
D_0	Pre-exponential factor
IMC	Intermetallic compound
k_B	Boltzmann constant
MAE	Mean absolute error
N_A	Avogadro constant
Q	Activation energy
R	Gas constant
T	Absolute temperature
t	Aging time
$\overline{x^2(t,T)}$	Mean square diffusion distance
$x(t,T)$	Intermetallic layer thickness
x_0	Initial intermetallic layer thickness

2. Materials and methods

2.1. Experimental

Since the eventual goal of this investigation is to describe and model the kinetics of the IMC growth within PV module solder bonds, the experimental part requires systematic isothermal aging of soldered interconnections at various temperatures, and measurement of the IMC layer thickness at defined time steps. Therefore, the front busbars of industrial, mono-crystalline solar cells are interconnected using Cu ribbons with the solder coatings Sn60Pb40 and Sn41Bi57Ag2. For the interconnection process a semi-automatic contact soldering station is used, that is depicted in Fig. 1a. The most important material properties and processing conditions are summarized in Table 1.

Then, the interconnected solar cells are cut, embedded, mechanically ground and polished to obtain metallographic cross sections [12]. The samples are divided into four groups which are isothermally aged at temperatures between