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A strategy for implementation of triangular thin-film photovoltaic modules

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Abstract

In this paper we explore the possibilities of implementation of triangular thin-film photovoltaic modules. A concept of "balanced strip pairs" based on a coupling of photovoltaic strips of different lengths is proposed. This concept provides a uniformity of current output of all individual cells, and could be easily implemented with widely used monolithic integration with some additional wiring. One of the additional advantages of this concept is a freedom in designing the module's output voltage. As a reference to the proposed strategy a division of the triangular photovoltaic module into trapezoid cells with the equal area is presented.

Keywords: Triangular module; Photovoltaics; Thin-film; Current matching

1. Introduction

A strong technological push of the thin-film photovoltaic (PV) technology is causing a steady rise of the efficiency and the decrease of the price of the thin-film PV devices during the last decade. Although the crystalline silicon PV still has a dominant market share, there are some applications in which the use of thin-film PV technology is preferable. These applications mostly exploit the flexibility of the design of thin-film PV modules, which provides better integration possibilities. Unlike the crystalline silicon solar cells, which are uniform in size, the thin-film based solar cells can be of arbitrary shapes and sizes. Although the rectangular shapes are unmatched in achieving the optimum efficiency, the possibility of having PV module of different shapes is desirable for the applications in products from creative industry, such as building integrated photovoltaics (BiPV) (Jelle et al., 2012; Yoon et al., 2011) and product integrated photovoltaics (PiPV) (Reich et al., 2011), where besides the pure efficiency one must take care of the overall product design and visual appeal. The thin-film solar modules characterizes a uniform dark appearance, often regarded as more appealing than the conventional crystalline silicon solar modules, which is an important advantage for BiPV applications (Farkas and Horvat, 2010).

Moreover, the thin-film solar cells can be grown on flexible substrates, such as polyimide, or stainless steel, which enables them to be embedded in the curved surfaces, thus drastically improving their integration capabilities. The encapsulation of the flexible thin-film modules must also be flexible, and light-weight. Different plastic materials are used as encapsulants (La Notte et al., 2014; Morlier et al., 2013), enabling the application of the flexible PV modules in temporary objects or modular light-weight

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buildings. However, since the requirements of flexible encapsulant are demanding (flexibility, transparency, moisture barrier, etc.), currently there is no commercial material for projected lifetimes of 20–30 years.

There is virtually no relevant scientific literature which explores the possibility of implementation of the triangular thin-film PV modules. The applications in which the availability of triangular modules presents a great advantage are the mentioned BiPV products, and more especially as PV skin for geodesic domes with all triangular faces (Porta-Gandara and Gomez-Munoz, 2005). Currently some commercial triangular modules can be found on the market (Red Electrical, 2015; Trinergia, 2015), all based on crystalline silicon technology where PV module is made by tiling the regular silicon solar cells.

In this paper we present a strategy for the design of triangular thin-film PV modules. First, a strategy based on the division of the module into cells of the equal area by straight cuts is presented, and the drawbacks of such method are discussed. Then, we introduce the "balanced strip pairs" strategy based on division of the module into series of strips of equal width, and pairing of the strips in order to have perfectly matched current output. This strategy shows a great flexibility in adapting to the different module sizes and voltages.

2. Description of the used model

2.1. Thin-film monolithic integration

In the fabrication of thin-film PV modules the monolithic cell integration is widely used. It is a method for making serial interconnections between the neighboring cells (bottom contact of one cell is connected to the top contact of the neighboring cell). In this way the whole PV module is divided into a series of cells with a certain freedom in the design. The monolithic integration is achieved by making a series of laser scribes which define the individual cell edges (Wehrmann et al., 2012). It is preferable to have interconnection "dead space" length as short as possible. The length of the total interconnection has been reduced to less than 200 μm (Kushiya et al., 2009).

As it is known from the electrical circuits' theory, the voltage output of the monolithically integrated module is the sum of all cells' voltages, while the current of the module is equal to the lowest output current of the connected cells. In this way a cell with the lowest current output presents a performance bottleneck of the whole PV module (Fornies et al., 2013). In the most extreme case, when forced to operate on the higher current, reverse-biased mismatched cells dissipate the current as a thermal energy, which leads to cell degradation and severe decrease of the module's lifetime. Therefore it is strongly desirable to have all the cells in the serial connection with the same current output for the same insolation levels. This consideration is important in all types of solar modules, when serial connection between the cells is achieved. However, it is the most crucial with the existence of freedom to design cells with different shapes and sizes, as it is the case with thin-film PV.

Thin-film PVs use transparent conductive oxide (TCO) materials as an electrode through which the light can reach the absorber layer (Rowell and McGehee, 2011). These materials must provide both good optical transparency and electrical conductivity, which are both dependent on the thickness of the layer, but in the opposing manner. Due to the limited conductivity of the TCO layer acting as a current collecting electrode the length of the cells (the highest distance from the interconnection bus) must be kept below several mm. In order to overcome this limitation, a combination of monolithic integration with metallic current collecting grid (e.g. screen-printed or ink-jet printed silver) placed on top of TCO layer could be applied.

2.2. Numerical modeling details

In our study we will demonstrate the performance of a triangular photovoltaic module, in dependence on the shapes, dimensions and interconnection of the cells it contains. The simulations were done on an example of a right-angled triangle ABC (the angle between A and B is 90°), with the following dimensions: $A = 0.62$ m, $B = 0.86$ m and $C = 1.06$ m, but the shown principle is not limited to this module size.

The modules in the showed example are based on highly-efficient Cu(In,Ga)Se_2 (CIGS) thin-film technology, and the principle is not limited to this type of thin-film solar cells. The simulations were done on an example of an optimized solar cell on flexible polyimide substrate with 18.7% efficiency ($J_{SC} = 34.75\ \text{mA/cm}^2$, $V_{OC} = 711.9$ mV, FF = 75.75%) (Chirila et al., 2011). The simulation was done base on the measured J–V curve from the referred literature origin. We used a commercial software package for finite element method numerical simulation (COMSOL, 2015).

The numerical model consists of the TCO layer fed with the photo-current from the bottom side, and metallization grid placed on top of the TCO layer. The metallization grid is connected to the external circuit at which the voltage can be swept in order to obtain the I–V curve of the individual cell (or module). The sheet resistance of the bottom electrode is around two orders of magnitude lower than the sheet resistance of TCO, since it does not have to satisfy the transparency condition. Therefore, the series resistance caused by the bottom electrode was not considered in the used model. This modeling approach enables the simulation of solar cells with arbitrary shape and metallization geometry (Bednar et al., 2015), and also supports the simulation of curved PV modules (Bednar et al., 2014).

The cells in the module are serially interconnected by the described monolithic integration process. For the cells with length larger than several mm, the metallization grid was applied on top of the TCO layer in order to better collect the generated photo-current. The applied metallization grid has the form of parallel 250 μm thick silver finger lines. The