Solar Energy Materials & Solar Cells 113 (2013) 201–219

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Numerical modelling and experimental validation of a low concentrating photovoltaic system

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ARTICLE INFO

Article history:
Received 5 September 2012
Received in revised form
16 January 2013
Accepted 22 January 2013
Available online 21 March 2013

Keywords:
Non-uniform illumination
Concentrator solar cells
CPV
Electrical characteristics
Finger design
Metallisation

ABSTRACT

Concentrator solar cells need to be designed optimally depending on the concentrating photovoltaic (CPV) system, application and operating conditions to ensure the best system performance. The important factors while designing include concentration ratio, cell material properties, expected operating temperature, cell shape, bus bar configuration, number of fingers their size and spacing. The irradiation incident on the solar cell while being concentrated experiences several losses caused by the different physical phenomena's occurring in the system. A particular issue for CPV technology is the non-uniformity of the incident flux on the solar cell which tends to cause hot spots, current mismatch and reduce the overall efficiency of the system. Understanding of this effect and designing the cell while considering these issues, would help in improving the overall performance of the system. This study focuses on modelling a low concentrating photovoltaic system used for building integration, optimising the cell metallisation and analysing the effects of temperature on the overall output of the system. The optical analysis of the concentrator is carried out using ray tracing and finite element methods to determine electrical and thermal performance under operating conditions. Furthermore, an analysis is made to understand the effects of non-uniformity on the output of the device. About 0.5% absolute drop in solar cell efficiency was observed due to non-uniformity at 5° incident angle. A relative drop of 1.85% was observed in the fill factor due to non-uniformity of the flux distribution. A maximum cell temperature of 349.5 K was observed across the cell in both uniform and non-uniform conditions under an incident solar radiation of 1000 W/m^2 which further reduced the performance of the solar cell. The solar cell design was also analysed by varying the number of fingers and the optimum grid design reported. A small prototype concentrator based on the design proposed was made using polyurethane and tested experimentally with the optimized solar cell design. On comparing the results obtained using the experimental data a good agreement in the system output could be seen. The difference in the overall system output was seen to be of the order of 11% which could be due to several losses occurring in the prototype which were not accounted in the model.

1. Introduction

Solar cells are expensive even today when we would compare them with conventional sources of energy. CPV offers the best use of the silicon material for manufacturing solar cells which would otherwise be used in making simple flat plate PV modules. Concentrating sunlight using cheaper optical systems onto smaller cells, CPV offers the potential of increasing the electrical output by several times while using the same amount of silicon solar cells. The concentrating photovoltaic systems are classified based on their level of concentration usually described as concentration ratio (CR). The concentration ratio can be defined as the number of times the solar radiation is magnified by using the optical element on a solar cell and is mathematically expressed as the ratio of the area of the optical element aperture to the solar cell area. The amount of sunlight incident on the solar cells is rated on the basis of suns ($\times$) where 1 $\times$ corresponds to standard illumination at AM1.5, or 1 kW/m^2.

The CPV systems consist primarily of an optical concentrating element which could be a Fresnel lens [1–3], parabolic troughs [4], dishes [5,6], v-groove mirrors [7–9], luminescent glass [10–12], refractive prism [13–15] or a compound parabolic concentrator [16–21]. Other elements of the system include solar cells and a heat dissipation system. Systems operating in the range of 2 $\times$ –10 $\times$ are usually referred as low concentrator photovoltaic (LCPV) systems. These LCPV systems find their application into building integration [16,18,22], and are expected

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http://dx.doi.org/10.1016/j.solmat.2013.01.035

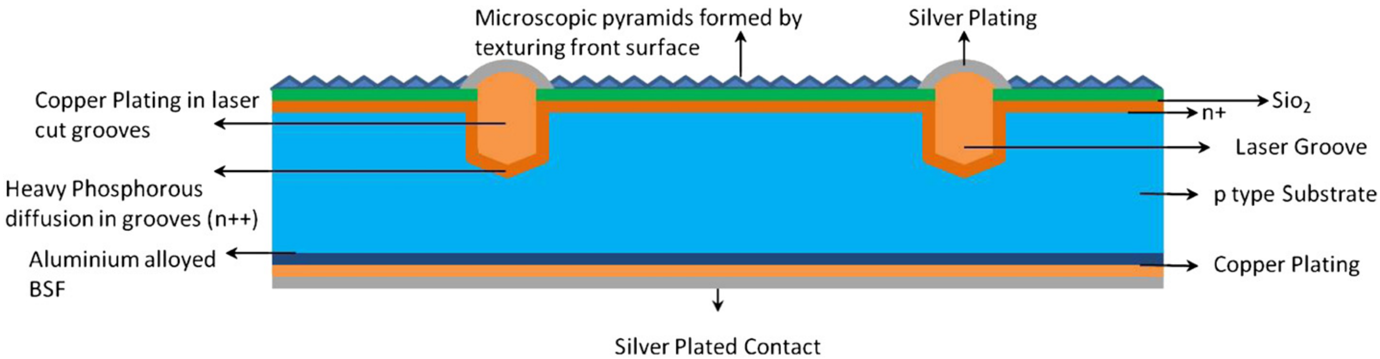

Fig. 1. Schematic diagram of a LGBC solar cell structure [28].

to expand their market in the near future. Usually CPV systems are designed for operating under high direct normal incidence (DNI) and so use tracking arrangements. However for low concentration applications the optical element can concentrate both direct and diffuse part of the solar radiation, when making use of non-imaging optics [23]. Designing the optical element of such systems involves performing detailed ray trace simulations which lead towards understanding their optical performance and predicting their overall efficiency.

Once the light is concentrated by the optical element, it is incident on the solar cells whose sole purpose is to convert this solar irradiation to electrical energy. Hence, the solar cell is usually referred to as the heart of the CPV system. Depending on the concentration ratio, application and the type of concentrator different types of solar cells are utilized for having an optimum performance and reliability of the system. The type of solar cells to be used in the CPV system can be single junction silicon cells [16,18,24–28], thin films [29] or multi-junction cells [26,30–32]. Silicon cells are of various types; however, for concentration systems laser grooved buried contact (LGBC) solar cells are found to be more suitable [33]. LGBC solar cell technology is now widely used for solar cells used in both low and medium (up to 100 $\times$) CPV applications. More than 18% efficiency can be obtained on monocrystalline Czochralski (CZ) silicon wafer using effective design and manufacture. LGBC cells were developed in the 1980s, since their inception they have undergone numerous upgrades to improve their performance. Fig. 1 represents the cell structure of a typical LGBC solar cell. The silicon wafers are initially etched to form the pyramidal front surface. A light uniform phosphorous emitter is diffused into the front surface, followed by the deposition of a silicon nitride anti-reflection coating.

The solar cells front contact pattern is defined by carrying out a laser grooving operation. The crystal damage from this process is removed by a wet chemical process and a heavy phosphorous diffusion is done into the laser groove. An aluminium back surface field is created on the rear surface by aluminium deposition and thermal processing. Front and back contacts are formed simultaneously by electroless plating nickel, copper and silver. Finally an edge isolation pattern is defined on the rear of the cell to define the shape of the cell and to ensure the cells have a high shunt resistance.

Typically, the front metallization of these cells consists of a set of fingers and busbars. These cells are made in high volumes and are very reliable. They can have a selective emitter and very small finger spacing's resulting in lower emitter resistive losses and lower contact losses.

Concentrator cells differ significantly from conventional screen printed one-sun cells in several ways, including the method of manufacturing process, the overall cell design and their

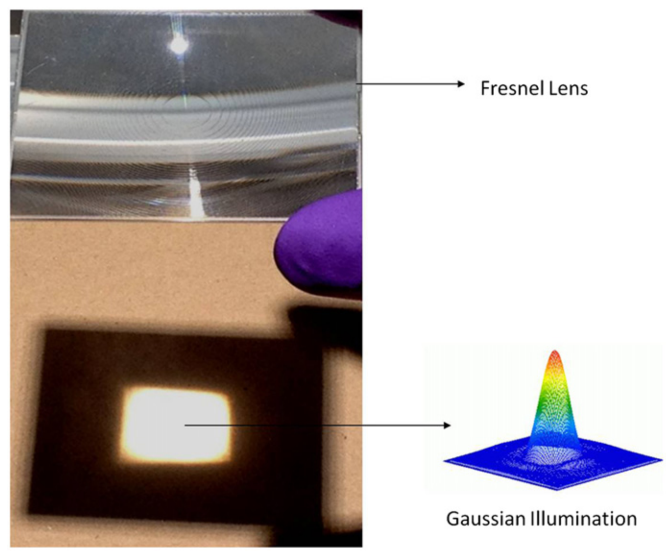

Fig. 2. Illumination produced by using a Fresnel lens.

performance. The concentrator solar cells generally include bus bars around the perimeter of the cell which can be accommodated without blocking any of the incoming light [34]. The cost of the concentrator solar cells plays the most important role in making CPV technology feasible. Improvements [28] in material quality having longer minority carrier lifetimes, proper grid design, enhanced light trapping and improved surface passivation can further lead to the development in this technology.

The high irradiance caused by using an optical concentrator improves the efficiency of the solar cells, which is again limited due to losses caused by the increase in series resistance losses. These resistance losses are directly proportional to the square of the concentration levels under which they operate [28]. The main contributors to the losses include the emitter sheet resistance, the resistance of the gridline and the contact loss at the metal–semiconductor contact area and the resistance of the semiconductor material [35]. Whilst, requiring a different design process compared to conventional screen printed solar cells making them slightly more expensive than the conventional solar cells. Recent developments in order to improve the design and manufacturing process have been highlighted by [36]. However, one limitation these cells encounter is that they are capable of absorbing limited regions of the solar spectrum, which is not the case in multi-junction solar cells.

Solar cells only convert a partial amount of absorbed solar radiation into electrical energy; the remaining energy is