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Fabrication, characterization and modeling of a silicon solar cell optimized for concentrated photovoltaic applications

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ABSTRACT

Silicon is still an interesting material for developing Concentration Photovoltaic (CPV) cells working at low and medium concentration range. In this work we describe modeling, design, fabrication technology and functional characterization of a small-area silicon solar cell suitable for CPV applications up to 200 suns. Two-dimensional (2-D) numerical simulations by a state-of-the-art Technology Computer Aided Design (TCAD) tool adopting calibrated physical models have been performed for both cell design and deep understanding of its performance. Specifically, the simulations have allowed the development and optimization of front contact grid scheme and design of the cell operating under medium concentration. The cell has been tested by means of a novel indoor concentrator system up to 300 suns and a conversion efficiency higher than 22% has been measured, according to numerical simulations. The dependence of short-circuit current on concentration factor has been observed to be super-linear. An excess of short-circuit current at 300 suns of approximately 8% has been measured. The super-linear effect has been investigated by means of numerical simulations and explained in terms of enhanced carrier diffusion length under concentrated light. The dependence of the super-linear effect on the incoming photon wavelength was also observed and discussed, showing that the super-linearity is due to the spectrum portion above 600 nm only.

1. Introduction

In recent years, photovoltaic (PV) industry has been able to ensure a significant reduction of fabrication cost, making grid parity closer and closer. At the same time, PV market has faced a general arrangement, also due to changes in the feed-in tariff scenario that further pushed towards PV product with higher efficiency and lower production costs. In this context, concentrated photovoltaic (CPV) represents an emerging market with approximately 100 MW cumulative installed capacity at the end of 2012, 45 MW of which installed in that year [1]. There are two main factors behind this growing interest: (a) the economic advantage of reducing the amount of cell material per watt and (b) the exploitation of high-efficiency and custom-designed cells under concentrating light that are still too expensive to be used in non-CPV applications. The latter group includes the so-called high-efficiency silicon cells that are the focus of this study, as well as III–V multi-junction (MJ) cells. MJ cells, because of higher production costs, are used in high-concentration systems only, which have concentration factor between 300 and 2000 suns. I n this case, MJ cells ensure high efficiency up to 40% also at a so high solar concentration [2]. Unfortunately, high-concentration PV requires very complicated installations, since the use of high-concentrating optics, cooling systems, and very precise sun trackers are mandatory. However, the success of the whole system is a trade-off between efficiency and costs of both cells and concentrating systems: cells, optics and trackers must be realized with a low production cost having both high performance. In this scenario, medium-concentration CPV systems, which concentrate the sunlight between 40 and 300 times, coupled with high-efficiency solar cells based on silicon, can still have room available to play an important role.

In order to be competitive with MJ-based CPV, silicon-based CPV is required to win the challenge represented by the conversion efficiency increase under concentrated light in the range 100–200 suns, keeping low at the same time the whole system cost. There are for sure two main key aspects to take into consideration for this purpose. The first is that a solar cell, based on abundant and cheap material such as silicon, and produced by means of a simplified CMOS-like technology, could provide cells cost

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reduction in case of very large production regime. The latter refers to the tracker: since silicon cells can operate in medium concentration range (about 100–200 suns with passive cooling systems), the tracker can be less accurate in terms of precision, therefore allowing cheaper solutions with respect to those required for high-concentration CPV [3].

There has been a considerable effort in the past for proposing many different solutions for silicon based CPV solar cells [4–8]. By using fabrication procedure running in research lab it was demonstrated that back-contact cell schemes were able to improve efficiency up to 27% at about 100 suns [9]. Currently, the confirmed efficiency record for silicon concentrator cells is 27.6% at 92 suns reached by a back-contact cell developed by Amonix [2,10]. However, this technology requires both a relatively complex and expensive double-side fabrication process and high-quality silicon substrates with long bulk lifetime (in the millisecond range). Both these characteristics are not compatible with a cost-effective mass production.

The present work is focusing on the development of a silicon solar cell specifically designed for CPV, which is based on a simplified and reliable CMOS-like manufacturing process. The proposed technology is derived by a simple single-side planar cell scheme known as Passivated Emitter Solar Cell (PESC) [11], which has been redesigned for CPV. A similar technological approach was also proposed in [8], where a 21% efficient solar cell at 100 suns ready for mass production is presented.

In this work the cell layout has been properly optimized in order to maximize the conversion efficiency of such a cell for the medium concentration range. As results of the optimization procedure a cell with efficiency higher than 22% at 100 suns has been obtained. The development phase has required a careful evaluation of cell layout that has been approached with in-depth ad-hoc simulation study. The latter is based on two-dimensional (2-D) numerical device simulations [12], which correctly describe the cell electrical characteristics and its performance under concentrated light. The adopted device simulations account for state-of-the-art physical and electrical models (including doping and minority carrier density dependence of mobility, band-gap narrowing, Auger and trap-assisted recombination) calibrated by means of experimental data for a correct simulation of solar cells under concentrated light. These models correctly predict some high-injection effects such as the short-circuit current density (J_{SC}) super-linearity with the incident irradiance. Such property has already been observed in CPV silicon solar cells and partially explained in terms of electric field influence on collection efficiency [13]. In this work the J_{SC} super-linearity is further discussed and supported by simulations of internal quantum efficiency under concentrated irradiation. The described optimization procedure leads to design options and considerations that are significantly different from those successfully adopted for 1-Sun cells [14–17]. Thanks to accurate simulations a 22% efficient cell has been produced. The goal has been achieved by defining a cell structure, in terms of front metal grid layout and doping profiles, minimizing both the parasitic resistance, which potentially limits the conversion efficiency of silicon CPV solar cells, and the front surface metal coverage, which reduces the photo-generated current due to light shadowing.

The remainder of the work is organized as follows. In Section 2 the cell design, fabrication process with the adopted technological options as well as experimental characterization methods are described. In particular, the concentrator system, used in this work for indoor cell characterization, is outlined. This new system allows the characterization of small-size solar cells under concentrated light up to 500×. The most innovative characteristic of this system is the method used to set the light irradiance on test device. The system features a motorized diaphragm, and by simply changing the diaphragm aperture can tune the effective irradiance on the cell. This system supplies a fast and reliable way for measuring the cell efficiency as a function of concentration factor. In Section 3 a detailed discussion on the simulation methodology, including the optical and the device part, is presented. The numerical simulation flow is used to optimize the front contact grid design as outlined in Section 4. In Section 5 simulation and experimental results are compared and discussed. In addition, a detailed investigation of short-circuit current super-linearity on concentration factor is presented. Finally, in Section 6, the main achievements of the paper are summarized.

2. Materials, device fabrication and characterization

The cell has been fabricated at Micro-Nano characterization and fabrication Facility (MNF) of Fondazione Bruno Kessler (FBK, Trento, Italy), where a CMOS-like pilot line is available. The cell is based on a n^+pp^+ planar junction structure, commonly indicated as PESC [11,18,19]. This cell can be fabricated with three lithographic steps only, providing a simplified processing procedure. A schematic device cross-section is shown in Fig. 1. The front side is textured with random pyramids, *n*-type doped by phosphorus diffusion and passivated with a thin SiO_2 layer. Contacts are opened through the SiO_2 layer and the front metal grid is formed by means of sputtered aluminum. The cell back surface is *p*-type doped by means of a boron diffusion in order to form a Back Surface Field (BSF), then it is contacted with a uniform aluminum layer.

2.1. Fabrication process

The cell has been designed to be used in an innovative small-size mirrors based concentrator system working at 160 suns and described in Ref. [20]. The active area is $4 \times 4\ mm^2$ and the cell thickness is 280 µm. The cell is fabricated from p-type float-zone (FZ) silicon wafers, with a resistivity of 0.47 Ωcm. This value is expected to be a good trade-off between two effects: maximization of carrier lifetime in the bulk and reduction of series resistance losses introduced by the base region. Moreover, the FZ substrate supplies relatively high carrier lifetime also at low resistivity value and, with respect to the Czochralski silicon, avoids any efficiency degradation due to light exposure (light induced decay) related to the presence of interstitial oxygen atoms [21–23].

The principal steps of the fabrication process are summarized in Fig. 2. The process starts with a wet thermal oxidation (925 °C

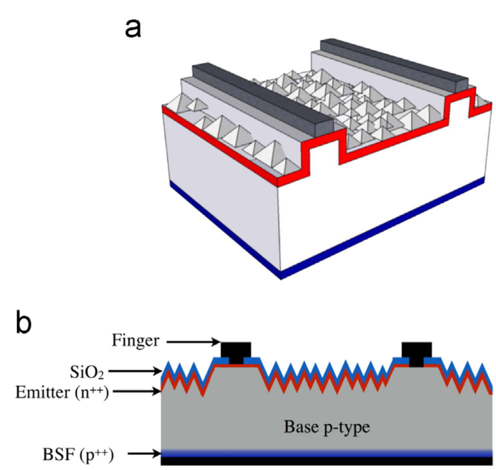

Fig. 1. 3-D Sketch (a) and vertical section (b) of the fabricated silicon solar cell (not in scale). The cell exhibits a pyramidal textured and oxide passivated front surface, while fingers, 6.5 µm wide, lie on planar surface. The silicon wafer is 280 µm thick and the back side is *p*-doped with boron.