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Fluorine- and tin-doped indium oxide films grown by ultrasonic spray pyrolysis: Characterization and application in bifacial silicon concentrator solar cells

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ABSTRACT

Multi-wire metallization and interconnection for silicon solar cells is considered as a revolutionary technology for the next generation of photovoltaic modules, since it drastically reduces their cost while boosting efficiency. In this paper, we report results obtained using an innovative approach for the fabrication of bifacial low-concentrator Ag-free Cz-Si (Czochralski silicon) solar cells based on an indium fluorine oxide (IFO)/(n^+pp^+)Cz-Si/indium tin oxide (ITO) structure. Transparent conducting oxide (TCO) layers, IFO and ITO, acting as antireflection electrodes, were grown by ultrasonic spray pyrolysis (USP). A copper wire contact pattern was attached by low-temperature lamination simultaneously to the front and rear TCO layers as well as to the interconnecting ribbons located outside the structure (laminated grid cell (LGCell) design). In this paper, to extend the operating range of sunlight concentration ratios of LGCells, the sheet resistance of the IFO and ITO layers has been reduced to 14 and 13 Ω/sq, respectively, by increasing their thickness by about three times, from ~85 to ~240 nm. As a result, the operating range of the LGCells has been extended to 1–7 suns. In the operating range, their front-illumination efficiency varies from 18.3 to 18.9% (back-illumination efficiency from 15.1 to 15.6%). We also report for the first time the results of systematic analysis of USP IFO properties and compare them with the USP ITO properties. The effect of the IFO thickness on grain size, electrical resistivity, charge carrier concentration and mobility, refractive index, transmission and absorption spectra, as well as optical band gap has been analyzed systematically by scanning electron microscopy, transmission and reflection spectra, optical ellipsometry and Hall measurements.

1. Introduction

To reduce the cost of electrical energy generated by crystalline silicon (c-Si) solar cells – the growth engine of photovoltaics (about 93% of the total production in 2016) (Burger et al., 2017) –it is necessary to reduce their manufacturing costs and raise the energy output of photovoltaic (PV) systems. For that, one needs to reduce or eliminate silver content used for metallization, because of high price for it and availability that in the future can be an obstacle for terawatt-scale deployment of c-Si photovoltaic technology (Tao et al., 2011). Various approaches have been proposed for reducing silver consumption. One of them is to use copper pastes (Yoshida et al., 2012), another is based on the electroplating of a Ni/Cu stack (Hernandez et al., 2013). In recent years, the ever increasing attention has been paid to the multi-wire approach, which uses many solder-coated wires instead of a few (usually three) busbars, and the wires are "soldered" to printed or electroplated fingers in the lamination process. The multi-wire approach allows silver consumption to be reduced owing to the less stringent requirements for the longitudinal resistance of the fingers (Braun et al., 2013). This technology is used by Meyer Burger AG (Smart Wire Connection Technology) (Soderstrom et al., 2013), and Schmid Group (multi-busbar design) (Walter et al., 2014).

Conversion efficiency is an important parameter that directly determines the energy output of a solar cell. However, increasing the efficiency of solar cells is typically accompanied by an increase of manufacturing costs, thereby making them less competitive. For this particular reason, the solar cells designed in the University of New South Wales (Green et al., 2012) exhibiting the record efficiency of 25% as of 1999 was not commercialized. Similarly, even though the solar cells manufactured by SunPower Co. and Sanyo Electric Co. were among the most high efficiency ones (Green et al., 2012), these companies were not market leaders. Remarkably, the market is dominated – with a market share of ~70% (as of 2016) – by solar cells made from cheaper, multicrystalline silicon (Burger et al., 2017), even though their

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efficiency is lower than that of Czochralski silicon (Cz-Si) solar cells. Thus, high efficiency of a solar cell design is an important but not decisive criterion for its competitiveness.

To increase the energy output of PV systems, alternative approaches are under development. In particular, one approach is based on the use of bifacial solar cells; the other is based on the concentration of sunlight.

Bifacial solar cells simultaneously collect photons from incident and albedo radiation reaching both the front side and backside of a solar module whereas the monofacial solar cells collect only those photons incident on the front side of the device. The effective albedo calculated with allowance for the solar spectrum, albedo spectrum, and spectral sensitivity of a solar cell ranges from $\sim$8% (asphalt) to $\sim$90% (snow) (Brennan et al., 2014). As a result, the increase in energy output may reach 50% (Guerrero-Lemus et al., 2016), depending on ambient conditions. This advantage of the bifacial solar cell may be characterized by its "equivalent efficiency" which is equal to the efficiency of a monofacial Si solar cell able to generate the same energy (Grigorieva et al., 2008). Accordingly, at an albedo in the range 20–50% the "equivalent efficiency" of a bifacial solar cell with a front/rear illumination efficiency of e.g. 18.1%/17.3% is 21.6–26.8% (Untila et al., 2014), i.e. at the level of the best monofacial solar cells. A number of manufacturers started commercial-scale production of bifacial solar cells (Burgers et al., 2011). Note, however, that these solar cells are not concentrator cells, because with increasing concentration ratio of sunlight (k_c) their efficiency decreases, e.g. from 19.6% at $k_c = 1$ sun to 15% at $k_c = 5.8$ suns (Untila et al., 2015a). An additional advantage of the bifacial solar cell over the monofacial is the reduction in the cell temperature due to the transparency in the IR range in the absence of the back metallization (Guerrero-Lemus et al., 2016). This advantage can be exploited most efficiently in concentrator systems (Guerrero-Lemus et al., 2016; Poulek et al., 2015). It should also be mentioned that some optical concepts of the sunlight concentration have been elaborated just for bifacial modules (Poulek et al., 2015).

Another possibility of reducing the cost of PV devices is based on using the concentrated sunlight since the efficiency of the cell could be increased by concentration, and parts of the solar cells which are the most expensive parts of PV system are replaced by much cheaper optical elements when using concentration technology (Xing et al., 2015). Although a high concentrator system (> 100 suns) can significantly reduce semiconductor usage, it requires accurate sun tracking and efficient heat dissipating systems, which increases the cost (Chen et al., 2013). In addition, the solar cells for high solar concentrating systems are generally highly expensive. Price for them exceeds about 100 times that for conventional flat plate silicon cells (Castro et al., 2008). The above problems can be solved by a low (2–10 suns) solar concentrating system with low cost and high efficiency silicon solar cells. Unfortunately, attempts to adapt standard screen-printed silicon solar cells for concentrator applications were accompanied by a considerable (a factor of 2–3) increase in silver consumption for making contacts (Chen et al., 2013).

Previously, we have proposed a solar cell design which is both bifacial and suitable for concentrator applications and ensures silver-free solar cell fabrication (Untila et al., 2000): laminated grid cell (LGCell) design, schematically presented in Fig. 1. The LGCell design is based on: (i) implementation of transparent conductive oxide (TCO) layers as antireflection coating as well as transparent and passivating electrodes on both, front and rear sides of a solar cell structure; (ii) copper wire based contact grids on both front and rear sides of a solar cell architecture by a low-temperature lamination technique at about 160 °C. In another design, a contact grid of solder-coated copper wires is attached to TCO layers using transparent conductive polymer (TCP) films (Chebotareva et al., 2017); and (iii) interconnecting ribbons in the proposed design are shifted from the solar cell surface and do not contribute to the shadowing of the solar cell structure (as a result, such design excludes a direct contact of a soldering iron with the solar cell structure, thus, avoiding its damage during the assembly into a PV module). The LGCells have been processed on the basis of p-Si as well as n-Si wafers. The LGCells had the following structure: In$_2$O$_3$:Sn (ITO)/(p$^+$nn$^+$)Cz-Si/In$_2$O$_3$:F (IFO) ("n-type" cell) and IFO/(n$^+$pp$^+$)Cz-Si/ITO ("p-type" cell). TCO layers were grown by a simple cost-effective process based on ultrasonic spray pyrolysis (USP). In these solar cells, the TCO layer thicknesses were equal to $\sim$85 nm. The operating range of light concentration for these solar cells was equal to $k_c = 1$–3.5 suns (Untila et al., 2012a,b) and $k_c = 1$–5.3 suns (Untila et al., 2013a,2014, 2015a).

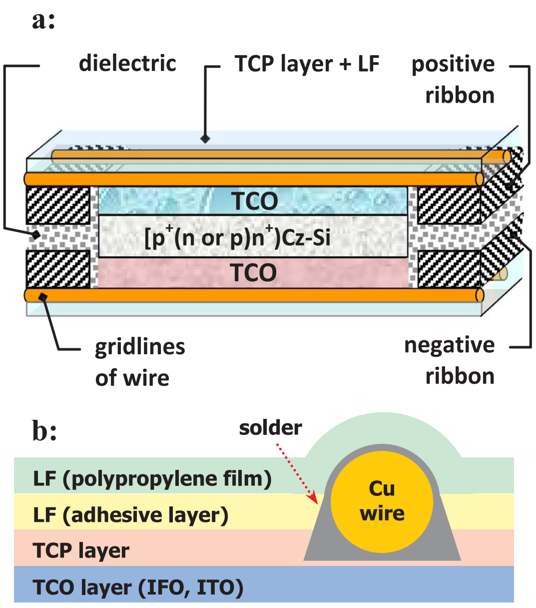

Fig. 1. Schematic of a bifacial LGCell: sections (a) along the wires and (b) across the lamination film (LF)/soldered wires/transparent conductive polymer (TCP) layer/TCO contact. Lamination film has the form of a 20-μm-thick adhesive layer on a 20-μm-thick polypropylene film (Untila and Zaks, 2011). See text for details.

It is worth noting that, unlike ITO layers, which have found wide application and have been studied in sufficient detail, IFO layers have been studied much less extensively: just sixteen papers addressing this issue were found in the Web of Science database (without our previous reports (Untila et al., 2008, 2009, 2013b)). IFO layers were prepared by a variety of techniques, including spray pyrolysis (SP) (Beji et al., 2016; El Hichou et al., 2009; Mirzapour et al., 1994; Rozati and Ganj, 2004; Singh et al., 1983), reactive ion plating (RIP) (Avaritsiotis and Howson, 1981), atmospheric-pressure chemical vapor deposition (APCVD) (Maruyama and Nakai, 1992); Mayer, 1992; Sheel and Gaskell, 2011), low-pressure CVD (LPCVD) (Miinea and Hoffman, 2000), magnetron sputtering (MS) (Shigesato et al., 2000), plasma enhanced reactive evaporation (PERE) (Ning et al., 2002), atomic layer epitaxy (ALE) (Asikainen et al., 1997). Analysis of the literature shows that only in our laboratory have IFO layers been grown by USP and studied from the viewpoint of using them in solar cells.

In this work, we extend the operating range of concentration ratios of LGCell bifacial concentrator solar cells to $k_c = 1$–7 suns by increasing the thickness of the IFO and ITO layers by about three times, which ensures a reduction in their sheet resistance. We also examine how the thickness of IFO and, for comparison, ITO layers grown by USP influences their main properties, in particular, on their grain size, resistivity, carrier concentration and mobility, refractive index, transmission and absorption spectra, and optical band gap.

2. Experimental

2.1. Test structures

TCO layers (ITO and IFO) were grown on the surface of the silicon structures (polished and textured) and of the Thermo Scientific

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