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Review

Top PV market solar cells 2016

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ABSTRACT

Photovoltaic (PV) technologies which play a role in PV market are divided into basic two types: wafer-based (1st generation PV) and thin-film cell (2nd generation PV). To the first category belong mainly crystalline silicon (c-Si) cells (both mono- and multi-crystalline). In 2015 around 90% of the solar market belonged to crystalline silicon. To the 2nd generation solar cells belongs thin film amorphous silicon (a-Si) or a combination of amorphous and microcrystalline silicon (a-Si/μc-Si), compound semiconductor cadmium telluride (CdTe), compound semiconductor made of copper, indium, gallium and selenium (CIS or CIGS) and III–V materials. The PV market for thin film technology is dominated by CdTe and CIGS solar cells. Thin film solar cells' share for all thin film technologies was only 10% in 2015. New emerging technologies, called 3rd generation solar cells, remain the subject of extensive R&D studies but have not been used in the PV market, so far.

In this review the best laboratory 1st and 2nd generation solar cells that were recently achieved are described. The scheme of the layer structure and energy band diagrams will be analyzed in order to explain the boost of their efficiency with reference to the earlier standard designs.

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Contents

1. Introduction

According to the Photovoltaic (PV) Market Alliance (recent report of 15th June, 2016) global PV markets should reach at least 60 GW in 2016 and more than 70 GW in 2017. Thus, by the end of 2016, total installations will reach 321 GW [1]. This forecast has been confirmed by the European Photovoltaic Industry Asso-

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ciation (EPIA) reports that the 540 GW mark at a global level could be reached by the end of 2019 [2]. The increase in installations is accompanied by falling prices of solar cells. PV Magazine reports that in June 2016 the price of the most efficient modules dropped down to 0.7€/W_p, while the mainstream modules (typically with 60 cells, standard aluminum frame, white backsheet and 245–270 W_p) cost only about 0.5€/W_p [3]. Here W_p stands for the module power at maximum power point for Standard Test Conditions. These numbers indicate that the PV market is growing rapidly and the prospects for the PV future are extremely promising.

PV technologies are divided into basic two types: wafer-based PV (called 1st generation PV) and thin-film cell PV (called 2nd generation PV). To the first category belong crystalline silicon (c-Si) cells (both single crystalline silicon and multi-crystalline silicon) and gallium arsenide (GaAs) cells. So far silicon solar cells have dominated PV market because of their mature technology. In 2015 around 93% of the solar market belonged to crystalline silicon with 24% – to monocrystalline and 69% to multicrystalline silicon solar cells [4]. Crystalline silicon's share has been rapidly growing during last few years due to the development of Chinese manufacturers.

Since solar cells were invented the scientists have been looking for absorber materials alternative to silicon. The current standard thickness of a crystalline silicon wafer is about 180 μm, but the aim is to reach lower thickness of 100 μm since the pure Si wafer creates the main cost of Si solar cells. Silicon in its pure form (of 99.9999% purity for solar applications) is very expensive and makes up about 20%–25% of the cost of crystalline panels. The thin film technology (2nd generation solar cells) provides alternative absorber materials, such as amorphous silicon (a-Si) or a combination of amorphous and microcrystalline silicon (a-Si/μc-Si), the compound semiconductor cadmium telluride (CdTe), a compound semiconductor made of copper, indium, gallium and selenium (CIS or CIGS) and III–V materials (GaAs, InP and AlGaAs). Solar cells made from these materials are called thin-film solar cells because the absorbers have the thickness of a few micrometers. The semiconductor cost of a thin film silicon is about 2% in thin film panels. The thin film solar cells take advantage in lower costs, but they generally exhibit lower efficiency than crystalline solar cells.

In Europe the PV market for thin film technology is dominated by CdTe and CIGS solar cells. The leader by far in thin film technology is First Solar whose cadmium telluride module manufacturing costs are less than those of most crystalline cell manufacturers.

In the laboratory, high concentration multi-junction solar cells achieve an efficiency of up to 46.0% today [5]. However, due to the high cost of their production, the only entry market is space applications.

Thin film solar cells' share for all thin film technologies was only of 10% in 2015 and it is predicted to drop down to 7% by 2017 according to International Technology Road Map for Photovoltaic (ITRPV) [6]. New emerging technologies, such as organic, dye sensitized, quantum dot and perovskite solar cells (called 3rd generation solar cells) remain the subject of extensive R&D studies but have not been used in PV market, so far.

In the article we shall focus on the best laboratory inorganic 1st and 2nd generation solar cells which are potential candidates for PV market. These are the recently announced top solar cells and those reported by Green et al. in the solar cell efficiency tables (version 48) [5]. The main criterion dictating whether these results were included in the Tables is that they must have been independently measured by a test center listed elsewhere [7]. This review presents current technologies for top high-efficiency 1st and 2nd generation solar cells. In particular the layer structure and energy band diagrams of the solar cells are analyzed in order to shed light on the progress of these technologies and origin of their efficiency improvement.

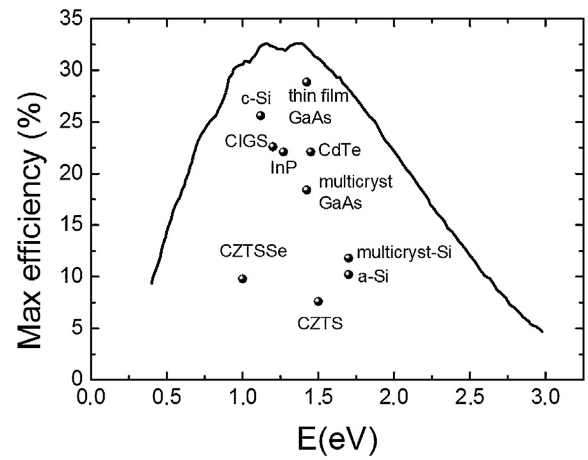

Fig. 1. S–Q efficiency curve for a single junction solar cell under AM1.5 illumination from Wiki page. The points represent the best experimental single junction cells fabricated to date.

1.1. Shockley - Quiesser limit

The efficiency of a solar cell is the main parameter characterizing its operation. The theoretical limit of efficiency for single-junction solar cells is usually referred to as the Shockley–Queisser (SQ) limit [8]. In Fig. 1, the maximum efficiency of a single-junction solar cell calculated using the Shockley–Queisser model as a function of band gap energy is shown. The calculations were made with the assumption that the incident solar spectrum is approximated as a 1.5AMO spectrum, and that one electron–hole pair is excited per incoming photon [9]. The points represent the best experimental single junction cells fabricated to date. In the article the reference to these solar cells is included.

2. Modern crystalline solar cell

Silicon solar cells have the advantage of using an absorber material that is stable, non-toxic, abundant and well recognized. It has an energy band gap of 1.12 eV, not far from the optimal value for a solar cell of 1.34 eV [9]. The record 25.0% power conversion efficiency for crystalline silicon solar cells was set by the University of New South Wales (UNSW), Australia, in 1999 [10,11]. This record was broken in 2014, when Panasonic, Japan [12] and SunPower, USA [13], announced independently certified efficiencies of 25.6% and 25.0%, respectively. The theoretical S–Q efficiency limit of a silicon solar cell is 33.5% with the assumption that the radiative recombination dominates [14]. However, silicon is an indirect band gap semiconductor so Auger recombination is dominant instead of the radiative recombination and this results in a lower theoretical limit. As it was shown by Richter et al. a maximum theoretical efficiency equals 29.43% for a 110 μm thick cell made of undoped Si [15]. As it is shown below, the matured technology of silicon solar cells provides the solar cells of efficiency larger than 25%, so it is close to the theoretical limit. Moreover, the efficiency of best modules is close – 24% [5].

The scheme of a conventional crystalline solar cell produced until 1999 is shown in Fig. 2. The cell is made of a p-type silicon wafer, also called an absorber, of thickness of 180–300 μm. N-type layer, called emitter, has much lower thickness (∼1 μm). This asymmetry arises from the fact that the carriers generated by the light must reach the junction area before they recombine. Therefore, the thickness of the emitter has to be on the order of diffusion length. The front metal contacts for the cell shown in Fig. 2 form a grid pattern. These contacts collect electrons. The holes are collected at the back contact. Since 1970 the technology of metal contacts is

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