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Silicon heterojunction solar cells: Recent technological development and practical aspects - from lab to industry

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ABSTRACT

We review the recent progress of silicon heterojunction (SHJ) solar cells. Recently, a new efficiency world record for silicon solar cells of 26.7% has been set by Kaneka Corp. using this technology. This was mainly achieved by remarkably increasing the fill-factor (*FF*) to 84.9% - the highest *FF* published for a silicon solar cell to date. High *FF* have for long been a challenge for SHJ technology. We emphasize with the help of simulations the importance of minimised recombination, not only to reach high open-circuit voltages, but also high *FF*, and discuss the most important loss mechanisms. We review the different cell-to-module loss and gain mechanisms putting focus on those that impact *FF*. With respect to industrialization of SHJ technology, we discuss the current hindrances and possible solutions, of which many are already present in industry. With the intrinsic bifacial nature of SHJ technology as well as its low temperature coefficient record high energy production per rated power is achievable in many climate regions.

1. Introduction

In recent years, an increasing number of silicon solar cells were reported that feature energy conversion efficiencies greater than 25% [1–6]. One key element that these solar cells all have in common is that passivating contacts are used for charge carrier collection. Such contacts enable high efficiencies through the reduction of recombination by the displacement of the metal contact from the silicon surface. One possible approach is the use of silicon heterojunction (SHJ) contacts formed by the deposition of hydrogenated amorphous silicon (*a*-Si:H) layers on the surfaces of the silicon absorber. Combining intrinsic *a*-Si:H layers (*a*-Si:H(i)) that provide excellent defect passivation at the silicon surface in stacks with p- or n-doped *a*-Si: H, enables the formation of selective and passivating contacts. The achievement of fill-factors (*FF*) well above 80% has been for long a challenge for SHJ solar cells in both academia and industry, while this was not the case for homojunction solar cells. Kinoshita et al. of the company Sanyo Corp. (now Panasonic Corp.) were the first to publish a *FF* above 80% in 2011 [7]. As can be seen from Fig. 1, at that time this was still $2\,\%_{abs}$ below the *FF* of the long-lasting world record obtained on a laboratory Passivated Emitter and Rear Contact[1] (PERC) solar cell ($FF = 82.9\%$ [8]). It took until 2013 that Taguchi et al. from Panasonic Corp. published a SHJ solar cell with a *FF* of 83.2% [9], exceeding the *FF* of the laboratory PERC cell. The efficiency of the cell reported by Taguchi et al., however, was still below 25% as a result of a relatively low short-circuit current (J_{SC}). The most common approach to attain the highest possible J_{SC} of solar cells is to place both carrier collecting contacts at the rear side of the solar cell, avoiding both shadowing by the metal contact grid as well as parasitic absorption in the front contact layers. The latter is specifically limiting two-side contacted SHJ solar cells, due to the high absorption coefficient of *a*-Si:H in the visible spectrum. We discuss this issue (J_{SC} for two-side SHJ) in Section 2.3.1.

A challenge for back contacted SHJ solar cells is that only half of the wafer surface is available for contact formation. In combination with the general challenge to obtain low-ohmic contacts with SHJ this explains the reduction in *FF* of the IBC-SHJ solar cell presented by Masuko et al. [2] compared with the previous SHJ record [9]. Still, the application of an all-back-contact architecture led to an increase in J_{SC} and with an efficiency of 25.6% set a new record for c-Si solar cells in 2014 [2].

In March 2017, Kaneka Corp. published their work on IBC-SHJ with the first silicon solar cell exceeding 26% efficiency [10] with a *FF* of 83.8%. This high *FF* was enabled by a series resistance of only $0.32\,\Omega\,\mathrm{cm}^2$, demonstrating that very low-resistive contacts can be achieved also with SHJ contacts. Later in 2017, further progress in efficiency was reported, culminating at 26.7% [4]. This cell featured an

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[1] Also referred to as Passivated Emitter and Rear Cell.

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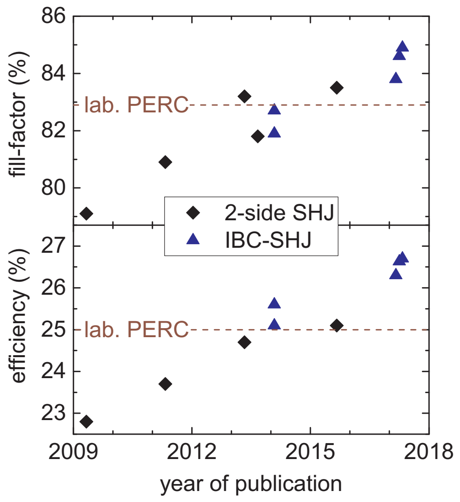

Fig. 1. Recent progress of efficiency and fill-factor for SHJ solar cells. For comparison, the long-lasting record of *c*-Si solar cells, a laboratory PERC cell [8], is included as dashed line.

even higher *FF* of 84.9%, enabled by its very low series resistance of only 0.2 Ω cm^2 [1]. To reach such high *FF*, not only transport losses have to be minimal but also recombination in low injection conditions, both in the silicon absorber as well as at its surfaces, needs to be sufficiently low [11]. These aspects were not covered in previous review articles [12,13]. The impact of recombination in the silicon absorber on the *FF* was covered by Leilaeioun & Holman, but the surface recombination was not considered in this paper [14].

Therefore, in this review, we put focus on recent progress of the *FF* in SHJ solar cells. After introducing possible SHJ device architectures in Section 2.1, we discuss the prerequisites to reach high *FF* with the help of the simulation of implied *JV* characteristics considering recombination both in the absorber and at its surfaces in Section 2.2.2. In Section 2.3 we review the loss mechanisms affecting the J_{SC}, V_{OC}, and *FF* of SHJ devices, including resistive losses into our calculations (Section 2.3.3). The impact of different interconnection technologies as well as binning of cells with slightly different JV characteristics on the *FF* of a module is discussed in Section 3, while possible challenges for mass production are covered in Section 4.

2. SHJ solar cell devices

Silicon heterojunction solar cells consist of a crystalline silicon wafer that is passivated on both sides with stacks of intrinsic and doped hydrogenated amorphous silicon (*a*-Si:H) layers. As the conductivity of intrinsic *a*-Si:H is very low, its thickness should be as low as possible, but a minimum thickness has to be retained to provide sufficient surface passivation (cf. Section 2.2.1). If at the front side,[2] also the thickness of the doped *a*-Si:H layer should be as low as possible to reduce parasitic absorption (cf. Section 2.3.1). To fully exploit the potential, high-quality silicon wafers featuring long charge carrier lifetimes have to be used. High efficiencies can be obtained on both doping types [15]. Nonetheless, most SHJ solar cells reported are based on n-type wafers due to its lower sensitivity towards impurities and the resulting superior charge carrier lifetimes [12].

With the very low surface recombination rates enabled by *a*-Si:H passivation, minority-charge-carrier lifetimes in the range of several milliseconds are obtained which enable open-circuit voltages well above 700 mV. At the front side, a metal grid is placed for charge carrier transport. Below the grid, usually a transparent conductive oxide (TCO) is needed to provide lateral conductivity. Other than with diffused junctions, the doped *a*-Si:H layers are laterally not conductive enough to fulfill this task. At the front side, the TCO serves also as an anti-refection coating (ARC). For stand-alone SHJ solar cells, its thickness is fixed to around 75 nm for optimal AR effect. When under glass, as in a module, this shifts to lower thickness.

2.1. Possible device architectures

To realize silicon heterojunction solar cells, different device architectures are possible of which the three most common are depicted in Fig. 2. All have in common that they are intrinsically bifacial, which can lead to 25–30% higher energy yield[3] [16,17]. In the front junction configuration (Fig. 2a), the minority charge carrier collecting contact is situated at the front side of the solar cell absorber. Here, the minority-charge-carriers are generated close to their collecting contact, which enables higher short circuit current density for short-lifetime absorber material. While this is explaining why the front junction configuration is currently the most widely-used one in industry (Al-BSF are such cells), it is of less importance for SHJ solar cells. As long as minority charge carriers can reach their collecting contact, high current densities can be obtained regardless of the position of the minority-charge-carrier contact. High charge-carrier lifetimes in the absorber and excellent surface passivation are a prerequisite to obtain this condition. Both are obtained in SHJ solar cells due to the excellent surface passivation of *a*-Si:H and the high-quality wafers used as absorber material.

Therefore, SHJ solar cells enable other device architectures, including with a minority-carrier-collecting contact on the rear side (Fig. 2c). Regarding SHJ solar cells, the rear junction[4] configuration enables the use of less conductive, and therefore more transparent TCOs at the front side as lateral current transport can also take place in the wafer [19]. Furthermore, the contact formation for holes in SHJ is often considered to be more delicate compared with the electron contact [20]. Thus, placing the p-contact on the rear side enables the use of different materials i.e. thicker or more highly doped at the cost of transparency which would be a drawback in standard configuration. Despite this theoretical advantage, we would like to point out that the highest reported efficiency of a two-side contacted SHJ (which is the highest-efficiency two-side contacted large-area silicon solar cell) was obtained on an n-type wafer with the *a*-Si:H hole-contact at the front [11,21].

However, for both aforementioned configuration, even assuming that fully transparent materials could be engineered to form the front contact, still a front metal grid is needed, which will lead to current losses due to shadowing. In order to tap the full efficiency potential, both contacts have to be placed at the rear side of the solar cell. This, in addition, further broadens the spectrum of possible contact materials used as neither thickness nor transparency are limiting the choice. The most common approach to realize such a cell architecture is to form the contacts for both polarities in an interdigitated pattern at the rear side of the solar cell, described as interdigitated back contacts (IBC, Fig. 2d). The omission of the thickness restraint for the doped layers results also in an increased robustness towards sputter damage and can be beneficial for contact formation and band alignment [22–25].

The major challenge for the industrial production of IBC devices is the cost-efficient formation of both contacts at the rear side of the wafer. Most IBC-SHJ devices reported so far rely on photolithograpy [26,5,27]. The *a*-Si:H layers are either structured by doping-selective etching in alkaline solutions [5,27] or using additional layers as etching barriers [26,28]. Laser structuring in combination with sacrificial layers has also been investigated [29–31], the highest reported efficiency is

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[2] The front side is the side facing the sun.

[3] Depending on site characteristics like albedo and row-to-row spacing.

[4] Often referred to also as so-called “rear emitter” configuration. As “emitter” is a misnomer regarding PV [18], we use rear junction as identifier.