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Theoretical evaluation of contact stack for high efficiency IBC-SHJ solar cells

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ABSTRACT

In this work we present a theoretical analysis of charge carriers transport mechanisms in IBC-SHJ solar cells. The concepts of contact and transport selectivity are correlated through the band bending at c-Si interface and are used to identify thin-film silicon parameters affecting fill factor (FF) and open-circuit voltage (V_{OC}). Additionally, the transport of carriers is associated to energy barriers at the conduction band for electrons and at the valence band for holes. In case of p-type contact, the transport of holes is mainly affected by activation energy and band gap of the p-type layer and work function of the TCO. In case of n-type contact, the activation energy and work function of the doped layer impact the most on transport of electrons. Selective transport is improved by maximizing the collection of majority carrier in each doped contact stack while blocking minority carriers. In particular, low activation energy values of doped layers are crucial to minimize energy barriers for majority carriers and increase the band bending at c-Si interface. Simulation results based on TCAD Sentaurus reveal that the FF increases as the activation energy of the doped layers is reduced. Also, for the p-type contact, the bandgap of p-type layer strongly affects the band bending at c-Si interface. Particularly, widening the bandgap of p-type layer enhances passivation and transport in terms of V_{OC} and FF but work function mismatch between the p-type layer and the related transparent conductive oxide (TCO) strongly increases as bandgap increases. This possibly makes the device less performant because it is more sensitive to activation energy of the p-layer in combination with the choice of the proper TCO. Considering realistic deposited layers, a wide bandgap p-type layer, in combination with low activation energy, potentially improves hole collection leading to maximal simulated FF = 86.8% and V_{OC} = 754 mV for a conversion efficiency η = 27.2%.

1. Introduction

Crystalline silicon (c-Si) solar cells dominates current photovoltaic market thanks to the material abundance, material stability, technological development and relatively high conversion efficiency [1]. Additionally, the photovoltaic (PV) market is pointing to the reduction of costs of generated power electricity by increasing solar cells efficiency. To achieve such an objective, research and development groups devoted several works on novel concepts to reduce device recombination losses and on advanced solar cell architectures [2]. Regarding solar cell architectures, interdigitated back contact (IBC) concept have constantly demonstrated record results [3–7] owing to the absence of front shading contact. Reducing contact recombination by means of passivating carrier-selective contacts concepts anticipate high open-circuit voltage (V_{OC}) well above 715 mV for high [3,8,9] and low temperature process [6,10–16]. Based on thin-film Si alloys, the use of silicon heterojunction (SHJ) structures has become particularly interesting to industry for the low thermal budget fabrication process. Besides, this PV technology benefits from the tremendous experience the field acquired from thin-film Si PV applications, which offer flexibility in a wide range of fabrication parameters [17–20]. The combination of c-Si and thin-film Si-based materials has therefore resulted in outstanding V_{OC} values between 740 and 760 mV [15,21,22], anticipating record efficiency solar cells. In fact, an IBC architecture with SHJ contact stacks has recently yielded the world record efficiency for c-Si solar cells (η_{record} = 26.6%) [21]. SHJ as passivating carrier-selective contact consists of the deposition of hydrogenated intrinsic amorphous silicon (i-a-Si:H) layer for chemical passivation followed by the deposition of thin-film silicon-based doped layers to form either electron-selective or hole-selective contact, thus inducing a potential on c-Si that allows carriers collection [23] (field effect passivation). Looking into thin-film Si portfolio, there is a broad list of thin films based on alloys of Si with carbon or oxygen in different phases (i.e. amorphous and nano-crystalline), leading to specific material parameters that are of particular interest to build efficient contacts [13,18,24–28]. Thus, it is essential to investigate parameters of thin films that stand out for high efficiency SHJ solar cells.

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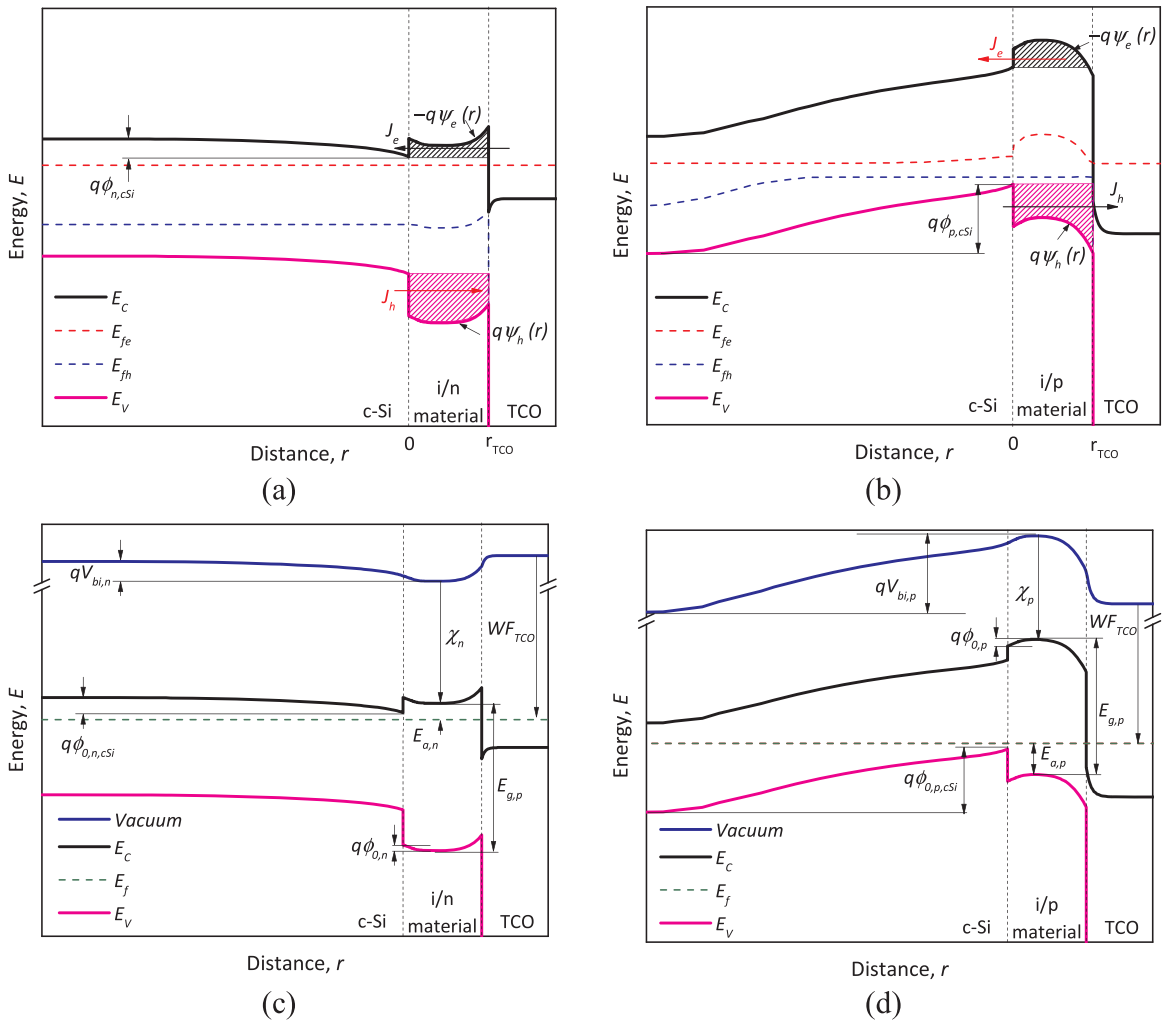

Fig. 1. Schematic band diagram of n-type (a) and p-type (b) contacts of a SHJ solar cell under illumination. Distance r = 0 is set at c-Si/i-a-Si:H interface. $E_{C,cSi}$ ($E_{V,cSi}$) and E_{fe} (E_{fh}) are conduction (valence) band energy level and Quasi-Fermi level of electrons (holes); $q\phi_{n,cSi}$ ($q\phi_{p,cSi}$) is the band bending at the c-Si / i-a-Si:H interface for n-type contact (p-type contact). Patterned areas stand for energy barriers for electrons in conduction band and for holes in valence band (see *Selective transport* section below). Schematic band diagram of n-type (c) and p-type (d) contacts of a SHJ cell at thermal equilibrium. E_f is the Fermi level at equilibrium; $q\phi_{0,n,cSi}$ ($q\phi_{0,p,cSi}$) is the band bending at the c-Si / i-a-Si:H interface for n-type contact (p-type contact) at equilibrium; $\phi_{0,n}$ ($\phi_{0,p}$) is the electrostatic potential supported by i-a-Si:H / n-type layer (i-a-Si:H / p-type layer) at equilibrium; $E_{g,n}$ ($E_{g,p}$) is the bandgap of n-type (p-type) layer and $E_{a,n}$ ($E_{a,p}$) stands for the activation energy of n-type (p-type) layer; χ_n (χ_p) is the electron affinity of n-type (p-type) layer. Here we assume that the total thickness of i/n or i/p stacks is larger than the sum of space charge regions from c-Si and from TCO. Then, $E_{f,n} = \chi_n + E_{a,n}$ and $E_{f,p} = \chi_p + E_{g,p} - E_{a,p}$. V_{bi} is the built-in voltage and W_{TCO} is the TCO work function.

In this context, earlier works on amorphous Si alloys studied carrier collection and passivation, identifying the doping in doped a-Si:H layers as crucial parameter [29,30]. Similarly, other groups devoted experiments on solar cell demonstrators, using nano-crystalline Si alloys and reporting similar improvements in V_{OC} and fill factor (FF) with respect to amorphous counterparts [31–33]. The improved induced potential was identified as the fundamental reason for V_{OC} enhancement [34]. Moreover, Adachi et al. remarked the path for high efficiency SHJ solar cells experimentally, showing that improving the passivation quality (V_{OC} enhancement), FF also increases [35]. Mechanisms ruling FF are typically related to solar cell resistivity losses, which are in turn linked to materials conductivity and contact resistance [36,37]. However, carriers' selectivity and transport at contact stacks can truly describe the inner physics of FF. To explain transport mechanisms, some theoretical works based of one-dimensional (1-D) numerical modelling have been previously reported, considering only thermionic emission as transport model at hetero-interfaces [38–41]. In this respect, TCO is typically modelled as a metal with a certain work function (WF), an approach that underestimates both tunnelling and transport at doped layer/TCO hetero-interface [42]. Concerning specifically IBC-SHJ solar cells, simulation works have limited the study to analyze properties of amorphous Si films [43,44].

In this work, we present first a detailed theoretical analysis of IBC-SHJ solar cell contact stacks to evaluate the competitive mechanisms of selectivity and transport towards optimal carrier collection. Afterwards, supported by advanced TCAD simulations, we identify key parameters of thin-film Si alloys impacting on both FF and V_{OC}. Finally, we provide general guidelines on the design of contact stack and rear geometry.

2. Selectivity and transport

The concept of selectivity refers to the ratio between the conductivity of majority and minority charge carriers in a doped layer [45,46]. The rationale is that selectivity accounts for collecting carriers inside c-Si absorber bulk in terms of carrier concentration at c-Si interface. Hence, within this work, with the terms *carrier selectivity* we indicate the collection of carriers at c-Si interface and with the term *transport* we describe the collection of carriers at the metal contact. Note that we use the following notation for subscripts related to contacts, carriers and materials: (i) n and p denote n-type or p-type contact