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Tunnel oxide passivated contacts as an alternative to partial rear contacts

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ABSTRACT

Recently, n-type Si solar cells featuring a passivated rear contact, called *TOPCon* (Tunnel Oxide Passivated Contact) were reported. The high conversion efficiency of 24.4% and very high $FF > 82\%$ demonstrates that the efficiency potential of this full-area passivated rear contact is as good as or even better than that of partial rear contact (PRC) schemes like PERL (passivated emitter and rear locally diffused) and in addition avoids complex structuring steps and features a 1D carrier transport. Likewise, a boron-doped passivated rear contact for p-type solar cells (p-TOPCon) is proposed as an alternative to p-PRC cells. The optimum device design of PRC cells has to account for two opposing effects: a low-loss 3D carrier transport requires a high base doping but Shockley–Read–Hall (SRH) recombination within the base due to the formation of boron–oxygen complexes in standard Cz silicon calls for a low base doping level. This conflict might be overcome by p-TOPCon because its performance is less sensitive to base doping. This will be discussed on the base of experimental results. It is shown that its high implied fill factor (*iFF*) of 84% combined with the 1D carrier transport in the base translates into a higher *FF* potential. First investigations on planar solar cells prove the good performance of the p-TOPCon with respect to passivation and carrier transport. A V_{oc} of 694 mV and a *FF* of 81% underline the efficiency potential of this rear contact.

1. Introduction

Today the industry is working towards the implementation of PRC [1] schemes in production. Recombination at the local metal-semiconductor contacts is a major source of device recombination which is significantly reduced by simply decreasing the metallized area fraction. However, V_{oc} and *FF* losses – the latter arise in particular from the 3D carrier transport at the rear (Fig. 1, left) – have to be carefully balanced by adjusting the pitch of the point contacts. For industrial p-type Cz silicon device optimization is even more complex because a low series resistance R_S, which requires high base doping for an efficient 3D transport, comes at the expense of significant SRH recombination caused by light-induced degradation (LID) [2]. Thus, the formation of boron–oxygen complexes constitutes a major efficiency limitation for these devices.

An appealing alternative to a point contact structure is a full-area passivated contact which decouples the absorber's passivation from the local metallization. In 1985 Lindholm et al. showed for the first time that heavily-doped polysilicon contacts can reduce the recombination at the rear side to some extent [3]. The benefit of applying polysilicon contacts to Si solar cells in terms of V_{oc}, i.e. J_{0e} was also demonstrated by others [4–6] and was recently revisited by Borden et al. (p^+-polysilicon/c-Si(n) junction) [7]. In contrast to a-Si:H based heterojunctions the polysilicon contacts are a viable option for conventional solar cells due to their higher tolerance to high-temperature processes. For instance, in Ref. [3] the polysilicon contacts were first realized on the rear side, then capped by a protective layer, and finally exposed to a diffusion process forming the front emitter.

In this work so-called tunnel oxide passivated contacts (TOPCon) for n-type as well as p-type Si solar cells are discussed. The TOPCon structure resembles the polysilicon contacts with deliberately grown interfacial oxide. In contrast to the polysilicon contacts, the TOPCon structure employs a wide bandgap semiconductor layer which contains amorphous and crystalline Si phases. For more details on the contact's morphology and structure as well as its implications on the blue response (parasitic absorption) the reader is kindly referred to Ref. [8].

The paper first addresses the passivated electron contact which was recently disclosed [9]. Due to its excellent carrier selectivity it enables high V_{oc} and *FF* at the same time which was demonstrated on an n-type Si solar cell featuring a boron-diffused emitter and

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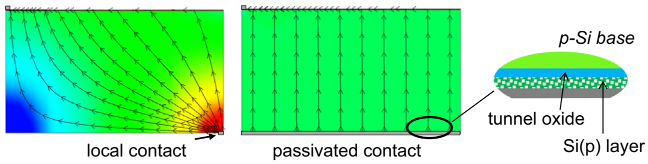

Fig. 1. Simulated current density of solar cells with local rear contacts and a passivated rear contact, respectively. The arrows indicate the minority carrier flow pattern.

the phosphorus (P)-doped passivated rear contact. In addition, its simple device design enables a 1D current flow in the base and thereby avoids *FF* losses originating from a 3D carrier transport (Fig. 1, right). Furthermore, it showed a high thermal stability and therefore could be integrated into a conventional diffused solar cell. Likewise, a boron (B)-doped passivated contact for p-type Si solar cells is proposed as an alternative to p-PRC cells which is investigated in more detail. Due to its one-dimensional device design, it might enable the use of lowly-doped wafers. Therefore, p-type cells featuring this passivated rear contact might be less prone to light-induced degradation. To this end, the interface passivation of p-TOPCon is studied on highly and lowly-doped p-type Si. Especially the implied *FF* (*iFF*), which describes the injection-level dependence of the passivation, will be discussed and compared to rear side passivation layers typically applied to p-PRC cells. Thereafter, the dark band bending, φ_0, induced by the passivated contact in the c-Si base is probed by means of the surface photovoltage (SPV) technique. It is a measure for the generated built-in potential V_{bi} of the p-TOPCon/c-Si(n) junction and can be used as an indicator for sufficient doping of the hole contact. Third, the passivated rear contact is integrated into a solar cell featuring n-TOPCon as emitter to facilitate the demonstration of its high V_{oc} and *FF* potential.

2. The passivated rear contact for n-type Si solar cells

The n-TOPCon rear contact for n-type Si solar cells [9] features a tunnel oxide grown in a nitric acid bath [10] and a P-doped Si layer. After deposition of the amorphous Si layer the contact is annealed at temperatures in the range of 800 °C to 900 °C and subsequently exposed to a 30-min hydrogen passivation process at 400 °C (remote plasma hydrogen passivation (RPHP)) [11]. Fig. 2 depicts the injection-dependent carrier lifetime curve for the n-contact after annealing at 800 °C and subsequent hydrogen passivation for symmetrical Si(n)/SiO_x/c-Si(n)/SiO_x/Si(n) samples. A high implied V_{oc} of 725 mV was obtained and corresponds to $J_{0,rear} \approx 7$ fA/cm². The J_0 values were calculated in the same manner as did in Ref. [9], where also the shortcomings of this method were discussed. However, this method is still very useful to later weigh the impact of front and rear recombination on the cell's V_{oc}. To assess the recombination limited *FF* potential of the passivated contact the *iFF*, which is a direct measure of the minority carrier recombination at maximum power point (MPP) conditions [12] is the relevant parameter for the electrical quality of the contact. The *iFF* is obtained in a similar manner as the pseudo *FF* (*pFF*) from SunsV_{oc} measurements [13] by using an implied *J–V* curve with the distinction that the iV_{oc} – calculated from the $\tau_{eff}(\Delta n)$ curve – is used instead of the V_{oc}. The difference between measured effective lifetime and the intrinsic limit, defined by the Auger recombination, is a measure of the quality of the passivated contact. Since the Auger limit is considerably higher at MPP than at open-circuit (OC) conditions, it is more difficult to approach this limit, i.e. obtain a very low minority carrier recombination at MPP, too. In this case a very high *iFF* larger 86% was obtained and underlines the excellent

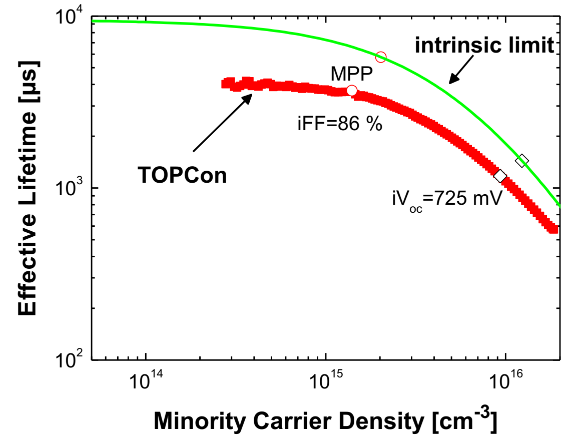

Fig. 2. Injection-dependent carrier lifetime curve of n-TOPCon after annealing at 800 °C, 1 h and hydrogen passivation.

Table 1
Overview of the champion efficiency of each solar cell generation. The n-type solar cells feature a boron-diffused emitter and the tunnel oxide passivated rear contact. The solar cell results except for the *pFF* were independently confirmed by Fraunhofer ISE Callab. The cell area is 2 × 2 cm² and the measurement condition is aperture area.

	V_{oc} (mV)	J_{sc} (mA/cm^2)	*FF* (%)	*pFF* (%)	η (%)
Gen 1	690.8	38.4	82.1	84.3	21.8
Gen 2	698.1	40.6	81.1	84.0	23.0
Gen 3	703.2	41.4	82.5	84.7	24.0
Gen 4	**715.1**	**41.5**	**82.1**	**85.0**	**24.4**

interface passivation over a wide injection range and thus a high *FF* potential of n-TOPCon.

The n-contact then replaced the locally diffused point contact passivation scheme of a high-efficiency n-type Si solar cell with boron-diffused emitter (140 Ω/sq) [14]. The development of these TOPCon cells is outlined and the light *I–V* and SunsV_{oc} [13] parameters of each generation's champion cell are given in Table 1.

Due to TOPCon's low contact resistance of ~10 mΩ/cm² and the cell's high *pFF* > 84%, high *FF*s above 82% were already obtained with the first generation. Thus, the *FF* gain compared to a similarly fabricated PERL cell is ~1% absolute [14]. Yet a strong parasitic absorption of light at the rear metal contact (titanium) caused a significantly lower J_{sc} [9] and, therefore, the maximum efficiency was just 21.8% (see Table 1). The insufficient light trapping
scheme was improved in a second generation (Gen 2) by replacing titanium with a silver rear contact resulting in a champion efficiency of 23.0%. A slightly higher V_{oc} was obtained by a reduction of the contact area of the metal front contacts from ~3% down to ~1.1%. However, the very high FF was partially sacrificed due to the poor contact resistance at the metal-emitter contact (ρ_c~9 mΩ/cm²). This series resistance contribution was drastically diminished in a third generation (Gen 3) by replacing the Ti/Pd/Ag metal stack for a Pd/Ag stack at the front. Owing to a low contact resistance below 1 mΩ/cm², the contact area could be reduced to ~1.1% enabling a high V_{oc} > 700 mV without sacrificing the high *FF* obtained in Gen 1. Therefore, excellent *FF*s of up to 82.5% were attained. In combination with some minor processing improvements, a champion cell with 24.0% conversion efficiency was achieved.

Although the n-TOPCon rear side provided excellent passivation quality, the V_{oc} of the Gen 3 cells is still similar to that of a PERL cell [14]. This can be ascribed to the recombination at the