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Fundamental consideration of junction formation strategies for phosphorus-doped emitters with J_{0e} < 10 fA/cm²

Byungsul Min[a,*], Jan Krügener[b], Matthias Müller[c], Karsten Bothe[a], Rolf Brendel[a,d]

[a]*Institute for Solar Energy Research Hamelin (ISFH), Am Ohrberg 1, 31860 Emmerthal, Germany*
[b]*Institute of Electronic Materials and Devices (MBE), Leibniz Universität Hannover, Schneiderberg 32 30167 Hannover, Germany*
[c]*SolarWorld Innovations GmbH, Berthelsdorfer Straße 111A, 09599 Freiberg, Germany*
[d]*Dep. Solar Energy, Inst. Solid-State Physics, Leibniz University of Hannover, Appelstr. 2, 30167 Hannover, Germany*

Abstract

This work shows the potential of further optimization of phosphorus-doped emitters in p-type silicon solar cells. We investigate the impact of different combinations of phosphorus doping profiles and surface passivation qualities on the saturation current density J_{0e} by considering boundary conditions based on published experimental data. Our simulation study shows that there are two possible ways to achieve J_{0e} values below 10 fA/cm². One is the reduction of the electrically active phosphorus concentration n_{surf} at the surface beneath 2×10^{19} cm^{-3} and simultaneously reducing the surface recombination velocity S_p to below 10^3 cm/s. The other contrarily increases n_{surf} to values of up to 1×10^{21} cm^{-3} while ensuring full activation of all phosphorus dopants. In the latter case, J_{0e} values below 10 fA/cm² seem possible, even for $S_p = 10^7$ cm/s which is equal to the thermal velocity.

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Keywords: emitter; recombination; passivation; junction formation

1. Introduction

In past years, the record efficiency of industrial p-type solar cells has been increased steadily towards 22% and above by applying the passivated emitter and rear cell (PERC) technology with reduced saturation current density J_{0e} in the passivated emitter region. An excellent J_{0e} value near 20 fA/cm² has been achieved with an industrial

* Corresponding author. Tel.: +49-5151-999-644; fax: +49-5151-999-400.
E-mail address: min@isfh.de

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process sequence and industrial equipment for a PERC cell with an efficiency of 22.1% [1]. For future efficiency improvements, the recombination losses in the base and at the rear side need to be further reduced. However, this will increase the recombination losses in the emitter again since reduced recombination losses in the base and at rear side lead to higher excess carrier densities and consequently to higher maximum power point voltages [1, 2]. Consequently, J_{0e} has to be reduced further towards 10 fA/cm² as suggested in Ref. [2].

Which boundary conditions need to be fulfilled for such low J_{0e} values? In order to answer this question we investigate the impact of different combinations of doping profiles and surface passivation qualities on J_{0e} by means of state-of-the-art device modelling. To achieve J_{0e} below 10 fA/cm², our modelling predicts two junction formation strategies. The electrically active Phosphorus concentration n_{surf} at the emitter surface has to be either reduced beneath 2×10^{19} cm^{-3} or has to be increased up to 1×10^{21} cm^{-3}. While the first approach requires excellent surface passivation quality with S_p values below 1000 cm/s, the second approach with n_{surf} near 1×10^{21} cm^{-3} enables J_{0e} values below 10 fA/cm², even for S_p equal to the thermal velocity, if phosphorus dopants are fully activated.

2. Approach

We investigate the recombination losses in phosphorus-doped emitters by simulating J_{0e} measurements with the device simulator SENTAURUS by applying most recent device models and silicon parameters [3, 4]. As doping profiles, we apply Gaussian profiles with varying surface doping concentration n_{surf} at constant sheet resistance R_{sh}. This is shown in Figure 1 exemplarily for R_{sh} = 120 Ω/sq. In order to investigate the influence of R_{sh} on simulated J_{0e}, we consider the following two R_{sh} values: (i) R_{sh} = 120Ω/sq for representing the phosphorus-doped emitters of currently produced industrial solar cells with screen-printed fingers and busbars; (ii) R_{sh} = 380 Ω/sq for solar cells with extremely low external series resistance due to advanced metallization techniques with advanced fine-line printing [2]. Furthermore, it is assumed that all dopant atoms are electrically active. At high doping concentration above $n_{surf} = 4\times10^{20}$ cm^{-3}, this assumption may not be valid for conventional $POCl_3$ diffusion process, but authors have reported full activation of the phosphorus atoms at carrier concentration of 10^{21} cm^{-3} using advanced chemical vapor deposition techniques [5, 6].

In addition, we vary the hole surface recombination velocity parameter for each Gaussian doping profile in order to analyze the impact of surface passivation quality on simulated J_{0e}.

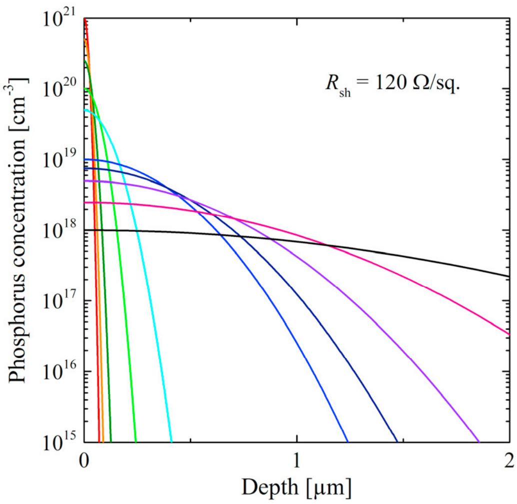

Fig. 1. Gaussian doping profiles with varying surface doping concentration n_{surf} at constant sheet resistance R_{sh} = 120 Ω/sq..

3. Results

The simulated J_{0e} values are plotted as a function of n_{surf} by varying the surface recombination velocity parameter for holes S_p as shown in Fig. 2. By decreasing n_{surf}, the values of J_{0e} depend significantly on S_p while J_{0e} values at surface doping concentration near 10^{21} cm^{-3} are nearly independent of S_p. Fig. 2(a) shows that J_{0e} values below 10 fA/cm² can be achieved with R_{sh} = 120 Ω/sq for following conditions: (i) for $n_{surf} < 2\times10^{19}$ cm^{-3}, the value of S_p needs to be similar to or lower than 10^2 cm/s; (ii) for $n_{surf} > 5\times10^{20}$ cm^{-3}, the value of S_p can vary between 1 and 10^7 cm/s depending on n_{surf}.

In contrast, R_{sh} = 380 Ω/sq allows J_{0e} values below 10 fA/cm² for any n_{surf} in he investigated range, if S_p can be kept below 100 cm/s as shown in Fig. 2(b). The reason is a decrease in the Auger recombination with increasing R_{sh} following from the reduced amount of phosphorus donors in the emitter. Unfortunately, it is well known in the literature that S_p depends strongly on n_{surf}, a subject which will be discussed in the next section.

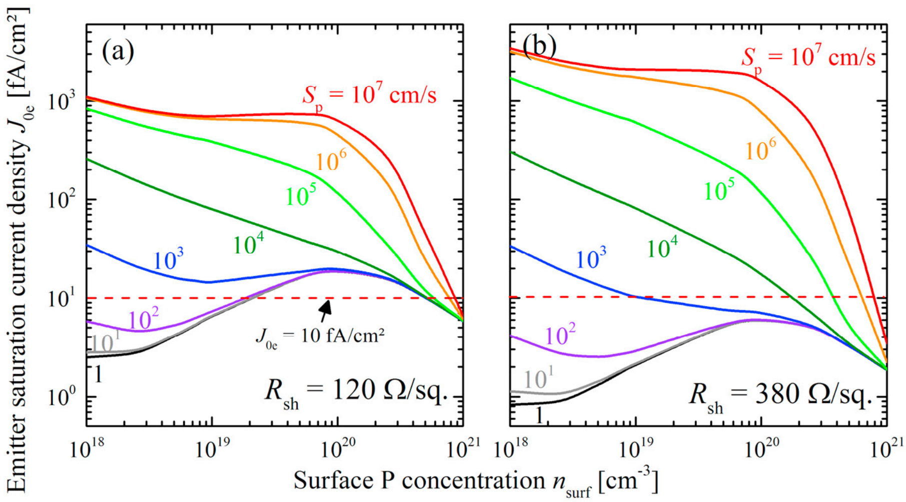

Fig. 2. Simulated J_{0e} values of Gaussian profiles with varying nsurf. The sheet resistance value was kept constant with (a) R_{sh} = 120 Ω/sq and (b) R_{sh} = 380 Ω/sq. The J_{0e} value of 10 fA/cm² is marked with a red dashed line.

4. Discussions

In our simulation study, we assumed that S_p values are independent of n_{surf}. However, it is shown experimentally that S_p increases monotonically towards high n_{surf}, regardless of which type of surface passivation has been applied as shown in Fig. 3(a).

By reviewing the measured S_p values of textured surfaces from literature (see Fig. 3a), we find the following correlation between S_p and n_{surf} for passivated emitters on textured surfaces: (i) S_p values below 10^3 cm/s have so far not been reported for n_{surf} above 1×10^{19} cm^{-3}; (ii) S_p values reach nearly 10^6 cm/s at n_{surf} near 2×10^{20} cm^{-3}. Therefore, only the simulated J_{0e} values with $S_p = 10^7$ cm/s are meaningful at n_{surf} near 1×10^{21} cm^{-3}. Consequently, we derive the following two strategies that allow J_{0e} values below 10 fA/cm² for both considered R_{sh} values. First, n_{surf} has to be reduced beneath 2×10^{19} cm^{-3} and simultaneously the value of S_p needs to be similar to or lower than 100 cm/s. Alternatively, n_{surf} is increased up to 1×10^{21} cm^{-3}. In this case, J_{0e} values below 10 fA/cm² are possible, even for $S_p = 10^7$ cm/s because the hole concentration at the surface is strongly suppressed. This can be explained by the increased effect of Pauli-blocking at high donor concentration N_D that leads to the exponential decrease of hole concentration for N_D above 1×10^{20} cm^{-3} as shown in Fig. 3(b).

The first approach with reduced n_{surf} is the common method that is currently applied in the PV community [7]. The reduction of n_{surf} beneath 2×10^{19} cm^{-3} can be realized with an etch back process after conventional $POCl_3$ diffusion or with advanced $POCl_3$ diffusion processes such as diluted source or low pressure diffusion technology.

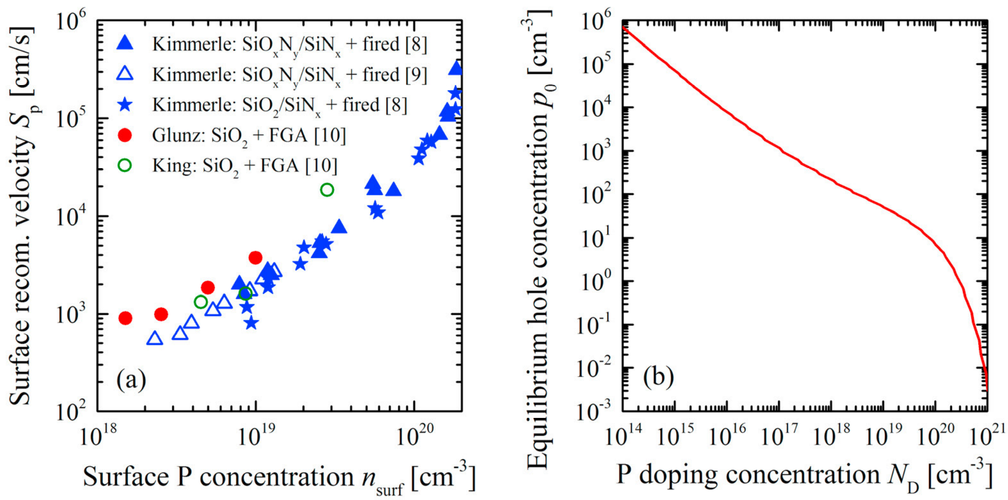

Fig. 3. (a) Surface recombination velocity plotted versus the electrically active Phosphorus concentration at textured surface for SiO_xN_y/SiN_x (triangles), SiO_2/SiN_x (stars) and SiO_2 (circles) passivated emitters. The values are extracted from various authors in Refs. [8-10]; (b) Equilibrium hole concentration p_0 as a function of the electrically active phosphorus doping concentration N_D.

However, the technical implementation of S_p values near 10^2 cm/s may be the major challenge, since the reported S_p values on textured emitter surfaces seem to saturate towards 10^3 cm/s for n_{surf} below 1×10^{19} cm^{-3} as shown in Fig. 3(a). An aluminum anneal may be a suitable candidate to realize such extremely low S_p values on textured emitter surfaces, since it allows generally lower S_p values compared to the passivation layers listed in Fig. 3(a) [10].

By contrast, the major challenge for the second approach with n_{surf} near 1×10^{21} cm^{-3} is the technical implementation of heavily-doped layers without electrically inactive dopants and process-induced defects. Advanced chemical vapor deposition (CVD) techniques such as photo-CVD or plasma-CVD appear to be most promising processes for its realization as demonstrated in Refs. [5, 6]. Since these kinds of heavily-doped emitters possess a great potential to reduce J_{0e} significantly, its recombination properties deserve deeper investigations. In addition, the silicon properties such as band-gap narrowing or mobility of holes at doping concentration near 1×10^{21} cm^{-3} should be investigated further in order to validate the simulation results in this study.

Nevertheless, heavily-doped emitters with n_{surf} near 1×10^{21} cm^{-3} seem to be very charming for solar cell applications, since it might allow extremely low J_{0e} values that are nearly independent of the surface passivation quality, because the minority carrier concentration is strongly suppressed in this region. Therefore, solar cells featuring such heavily-doped emitters might be resistant to ultraviolet degradation of surface passivation. Furthermore, it is possible to neglect the introduction of passivating buffer layers between the silicon and the metal contacts, since the J_{0e} values are below 10 fA/cm², even if setting S_p equal to the thermal velocity.

5. Summary

In this paper we identify the fundamental junction formation strategies for further improvements of phosphorus-doped emitters in p-type silicon solar cells. Our simulation study shows that the electrically active phosphorus concentration n_{surf} at the surface is the decisive parameter for controlling emitter recombination losses, if the full activation of phosphorus dopants is ensured. Therefore n_{surf} should be either reduced beneath 2×10^{19} cm^{-3} while ensuring excellent surface passivation quality or increased up to 1×10^{21} cm^{-3}. On the one hand, our study validates the common method of the emitter optimization by reducing n_{surf} and shows boundary conditions for its realization. On the other hand, our study may give a new direction for further optimization featuring heavily-doped emitters with n_{surf} near 1×10^{21} cm^{-3}.

Acknowledgements

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