

Effective Surface Recombination of p⁺-layer in p-type Silicon PERT Bifacial Cell

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SUMMARY

Boron doped BSF is evaluated as a critically important factor in high efficiency p-Si solar cell designing. Recombination losses pronounced as effective surface recombination, S_{eff} , are evaluated by simulation and experimentally. Spectral response analysis of n⁺-p-p⁺ solar cells with highly doped deep BSF (~1.6 μm) demonstrates a possibility of providing S_{eff} of 75±20 cm/s without surface passivation. Whereas S_{eff} for thick heavy doped p⁺ layers are determined mainly by recombination inside the layer, for thinner p⁺ layers the surface recombination is a critical factor. n-Si wafers symmetrically doped by thermal diffusion or by implantation of boron ions were used for experimental validation of simulation results of surface recombination contribution and its dependence of charge build in coating. The recombination parameters of the samples were measured using the photoconductivity decay method.

BACKGROUND

Technological difficultness in fabrication of the PERT type solar cells based on p-Si cause the attempts to substitute this cell type by others (like PERT n-type or PERC p-type cells). However, proper managing of p⁺-layer parameters should allow achieving high efficiencies and good bifaciality for p-Si PERT cells.

Effective surface recombination, S_{eff} , of the p⁺ layer of bifacial Si n⁺-p-p⁺ structure is critical factor controlling the main solar cell parameters: back spectral response, diode saturation current, J_0 , and therefore open circuit voltage, V_{oc} , as well as front and back efficiencies [1 - 6]. Contribution in the S_{eff} and J_0 is determined by the bulk recombination inside the doped layer and by recombination on its surface.

The doping concentration and the doping depth are affecting both recombination components. The data of [6] are an example of such influence, and they can be analyzed as evidence of dominating effect of recombination inside of the highly and deeply doped p⁺ layer on the S_{eff} of the bifacial cell back side. However, if maximal doping concentration is below the B solubility limit and the doping is not too deep, the surface passivation is desirable for reducing recombination losses and increasing the open circuit voltage of the cell.

Different types of passivating layers are useable [1-5]. One of the important differences in their properties is the built-in charge, which can be negative or positive. Silicon oxide layer grown by thermal oxidation provides an effective passivation of the n⁺-Si. The drawback of such a layer for p-Si passivation is a positive built-in charge which is typical for such a layer. The passivation layers of different materials are applied for p-Si surface passivation. Aluminum oxide is presently the leading passivation material for p⁺ layers [1, 3]. However, the optimal passivation method of the p⁺ layer resulting in minimal S_{eff} for given specific properties of the layer is not developed.

Effect of the p⁺ layer doping parameters (impurity concentration and profile) on S_{eff} and on passivation effectiveness, as well influence of surface coating nature and of a charge built-in in the passivation coating are the subjects of the current study.

SIMULATION

Several practically appearing B profile types produced during BSF formation are under discussion. Simulation using PC 1D program was carried out for describing the p⁺-layer limitations of V_{oc} as well as of S_{eff} in the p-p⁺ junction. One of the simulation series describes the effect of the deeply doped p⁺ layers. Thickness of the doped layer was assumed ~1.6 μm, maximal concentration varied in the range 4.10¹⁸ – 3.10²⁰ cm⁻³. The recombination parameters of n⁺ emitter and of the base region were assumed fairly high to not limit V_{oc} below 735 mV. The simulation results are shown in Fig 1 as V_{oc} (and S_{eff}) functions of recombination velocity on the surface of the doped layer.

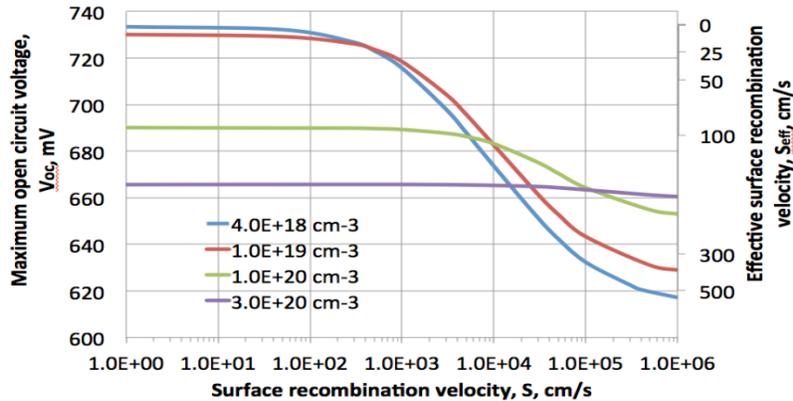


Fig. 1: Maximal open circuit voltage, V_{oc}, of n⁺-p-p⁺ PERT cell as limited by recombination parameters of the back p⁺ layer. Each curve refers to p⁺ layer with mentioned maximal doping concentration.

As can be seen, S_{eff} of the highly doped p⁺ layer with maximal concentration close to the B solubility in Si (3.10²⁰ cm⁻³ curve) is completely determined by bulk recombination in the doped layer and doesn't affected by recombination on the surface. Therefore V_{oc} doesn't depend on the surface recombination velocity which is not contributing in effective surface recombination. With declining the doping level an input of surface recombination in S_{eff} is increasing while the contribution of the doped layer bulk recombination is decreasing. These data illustrate the expected effect of surface passivation: no real need in passivation of highly doped deep layer and increased importance of passivation for lower doped p⁺ layers.

Simulation of the p⁺ layer effect was carried out also for the structures with shallower doping. Some results for the structures with p⁺ layers of ~0.8 μm are shown in Fig. 2. In this case the figure demonstrates effects on the resulting V_{oc} of two factors: of surface recombination and of the surface charge. The open circuit voltage is plotted as a function of the recombination velocity on the cell surface. Two groups of curves describe the structures with surface boron concentration, B_s, 10¹⁸ and 10²⁰ cm⁻³ for 3 different charge cases: positive charge, no charge or negative charge. Charge density Q (when present) is 2.10¹² cm⁻².

According to simulation, the bulk recombination in the relatively thin p⁺ layer doesn't dominate as much as in the thick one (Fig. 1), and surface passivation started to be more critical factor. However, the passivation effectiveness can be affected by the charge build in the passivation layer. Parameter controlling the influence of the charge on the S_{eff} is the B_s level. The charge in the passivation layer isn't influencing significantly when the surface doping concentration is relatively high, i.e. when B_s is above ~10¹⁹ cm⁻³. As can be seen, in the case of low B_s, both factors - the surface recombination and the charge - have significant influence on the V_{oc} (i.e. J₀ due to effect of S_{eff}). In this case the influence of charge becomes critical causing up to 40 mV losses even for surface recombination velocity of 10⁴ cm/s, which is fairly achievable with SiO₂ passivation. However, at high B_s the difference due to field effect of negative and positive fixed charge doesn't exceed ~10 mV at the same recombination velocity on the surface. So, at high B_s the charge has minor effect, and improvement of surface recombination (due to decreasing the dangling bonds density) is the controlling factor.

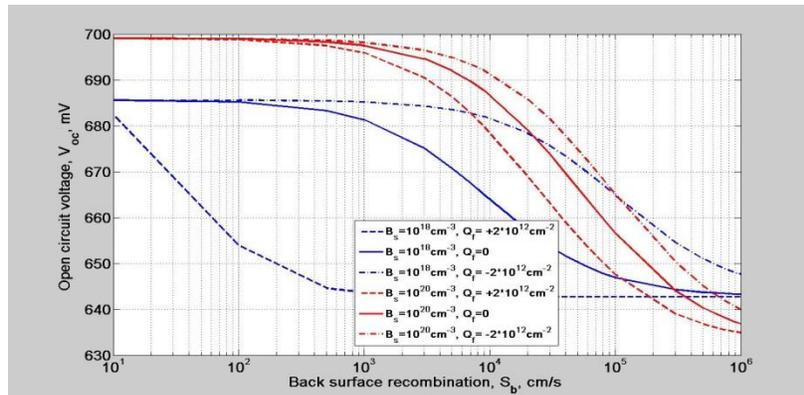


Fig. 2: Effect of B surface concentration and surface charge on open circuit voltage of the n⁺-p⁺ solar cell. p⁺ layer thickness is ~ 0.8 μm.

EXPERIMENTAL

The simulation results were proven experimentally. One series of experiments was carried out with the bifacial solar cells with thermally diffused back. The experimental basis of the simulation was the SIMS data for the diffused samples similar to heavily doped one shown in Fig. 3. The high B_s above the limit of solubility is distinguishing for deep doping profile.

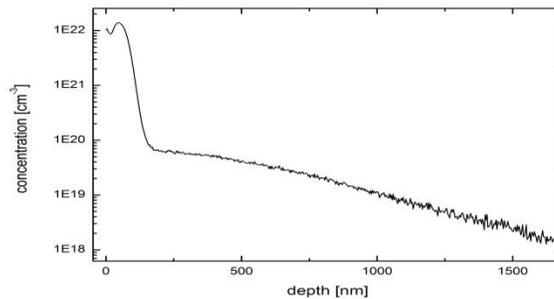


Fig. 3: The example of the boron SIMS profile after high temperature diffusion

The quantum efficiency of the back illuminated n⁺-p-p⁺ cells can be described using the S_{eff} values in the range 75±20 cm/s [6]. Comparison of curves in Fig. 1 with experimentally measured S_{eff} for deeply doped p⁺ layer demonstrates that the region with doping level lower than ~ 10²⁰ cm⁻³ contribute in S_{eff} value. It means that heavier doped regions near the surface don't add in S_{eff} of the thick BSF layers. This explains why the deep high B doped BSF have quite low S_{eff} (which is several times lower than Al BSF) and don't limit V_{oc} at the level lower than ~660 – 670 mV. And this is without any surface passivation.

Other experimental series include the n-Si samples symmetrically doped and passivated on both sides. The doping was carried by thermal diffusion using the controllable deposited B sources. The implantation of 30 keV B ions with subsequent annealing/redistribution high temperature step was also used for samples doping. Several passivation layers were tested: thermally grown SiO₂ alone or in combination with SiN, BSi alloy.

Wide spectrum of doping profiles with diffusion depth 0.6 – 1.2 μm was tested. Two examples of B profiles (which were prepared by 30 keV B ion implantation) are shown in Fig. 4. The samples were used as a basis for simulation illustrated by Fig. 2.

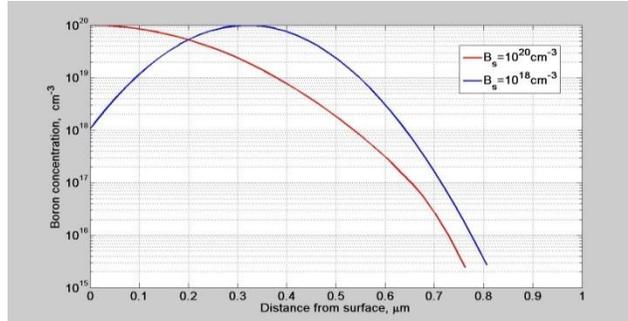


Fig. 4: Typical B distribution profiles used in simulation analysis of the charge influence on the S_{eff} . The profiles are in the range of experimentally prepared samples.

The lifetime measurements by photoconductivity decay technique were used for determination of S_{eff} . The measurements were carried out on the samples with dielectric layers, after thermal oxidation as well after surface cleaning and immersion in quinhydrone solution.

In accordance with simulation, the contribution of the surface in the recombination losses increases with decreasing of B_s and with thinning the doped layer. When doping is high, the thin layer of silicon oxide (of ~18 nm thickness) passivates the surface in about the same way as solution after RCA surface treatment. In the low doped p^+ layers the quinhydrone passivation is more effective than the positive charged oxide layer. The passivating effect of the very thin BSi layer (< 2 nm) can be seen. The preliminary experimental data are in the Table.

Table. S_{eff} for p^+ layers with different surface passivation

Sample #	Sheet resistance, Ω/\square	Junction depth, μm	Surface concentration, cm^{-3}	Effective surface recombination velocity, S_{eff} , cm/s		
				B-Si layer + Quinhydrone passivation	SiO_2 passivation	Quinhydrone passivation
Dif_55a	250	0.6	4E+18	16.3	74.4	3.7
Dif_50a	65	1.0	9E+18	4	47.7	48.9
Dif_60a	33	1.1	1.1E+19	45.6	40.9	14.4
lon_A	60	0.8	2E+19	-	125	140
lon_T	175	0.5	1.5E19	-	29.1	76.6

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