ELSEVIER Solar Energy Materials and Solar Cells 34 (1994) 117–123

Solar Energy Materials and Solar Cells

685 mV Open-circuit voltage laser grooved silicon solar cell

C.B. Honsberg *, F. Yun, A. Ebong, M. Taouk, S.R. Wenham, M.A. Green

Centre for Photovoltaic Devices and Systems, University of New South Wales, Kensington, NSW 2033, Australia

Abstract

The recombination limiting the voltage of the present buried contact solar cell (BCSC) can be reduced by replacing the present high recombination sintered aluminium back with a floating rear junction for passivation, heavy boron diffusion below the rear contact, and by limiting the rear surface contact area. Analysis of these implementations in the double sided laser grooved (DSLG) structure shows that the floating junction passivation is effective in reducing the recombination component at the rear surface and that the boron diffusion in the rear groove comprises up to half of the total saturation current. Limiting the area of the heavily diffused boron grooves allows open-circuit voltages of 685 mV while maintaining the simplicity of the BCSC processing sequence. An open-circuit voltage of 685 mV represents nearly a 50 mV increase over the conventional BCSC.

1. Double sided laser grooved structure

The buried contact structure has demonstrated both high efficiency and commercial compatibility [1–4]. The efficiency of the present buried contact solar cell (BCSC) is limited by the rear sintered aluminium contact. The rear Al surface is estimated to have a surface recombination velocity of 1,000 cm/s [5]. Replacing this high recombination area with a high voltage rear surface from the PERL or PERC structures demonstrates the efficiency and voltage potential for the BCSC. Such BCSC/PERL hybrids have achieved independently confirmed efficiencies of over 21% [6]. However, the use of high quality oxides for back surface passivation and photolithographically defined rear contacts makes these hybrids unsuitable to commercial production. The second generation of BCSCs represents a low cost

* Corresponding author.

SSDI 0927-0248(94)00023-L

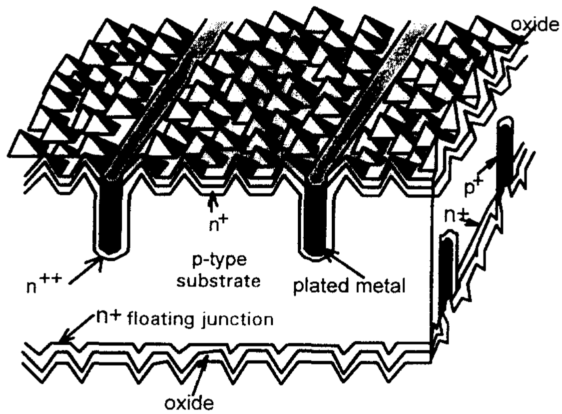

Fig. 1. Structure of the DSLG solar cell. Replacing grooves with wells and covering the rear with Al reduces the boron diffused area.

implementation of the BCSC/PERL hybrid [7] by using a floating junction for rear passivation and heavily p^+ diffused laser scribed grooves to contact the base through the floating passivating junction. Such a double sided laser grooved (DSLG) structure is shown in Fig. 1. The heavily diffused p^+ groove provides both a low resistance contact to the base and reduces the saturation current component from the metal contact.

2. Rear surface passivation using a floating junction

A floating rear junction allows for a well passivated back surface while still using the commercially compatible processing sequence of the BCSC. In the DSLG process, no extra high temperature steps are added. The floating junction is diffused at the same time as the front emitter and the addition of the boron diffusion for the rear grooves is balanced by the removal of the aluminium sintering step needed to make contact in the conventional BCSC. In addition, the vacuum evaporation step previously used in the rear aluminium contact is no longer necessary.

Modelling results indicate that the floating junction passivation is less sensitive to increases in the rear surface recombination velocity than using a back surface field (BSF) for passivation. Fig. 2 shows comparisons between BSF passivation and floating junction passivation based on PC-1D modelling of the DSLG structure. The device parameters are those used in the fabrication of the DSLG cell: substrates of 1 Ω cm, substrate thicknesses of 260 μm, and junction depths of about 1 μm. Fig. 2 shows that even if the rear surface is relatively poorly passivated, the V_{oc} from the solar cell is degraded less with a floating junction than with a back surface field. The reduced sensitivity to the back surface recombination velocity is especially important in a commercial process with textured surfaces.

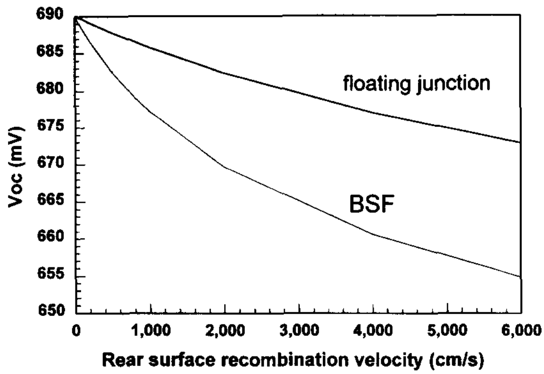

Fig. 2. Sensitivity of the rear surface recombination velocity for floating junction passivation and a diffused boron back surface field passivation.

The results from PC-1D are in general agreement with 2D simulation from PISCES [8]. However, the assumptions in [8] include higher recombination from the front emitter. Since the emitter and rear surface are identical, a cell with poorer front surface will also have reduced passivation available from the rear floating junction. Closed form calculations based on modelling the floating junction by a transistor structure such as in [9] also indicate that the relative advantage of a floating junction compared to an oxide passivated surface depends on the quality of the floating junction. In the DSLG process, the back junction is formed during the top emitter diffusion and so will be of the same quality as the front junction. Since the front surface has demonstrated high voltage potential in the BCSC/PERL hybrids, replacing the Al sintered back surface with a surface similar to that of the front of the solar cell yields a well passivated surface capable of achieving high voltages.

A possible disadvantage of the floating junction passivation is the fairly large area of heavily compensated material near the rear contacts. This could lead to a shunting between the floating junction and the base region which degrades the passivation properties of the floating junction. The simplified point contact structure [10] also incorporates heavily diffused and compensated regions. The high FF from these devices indicate that it is possible to reduce the shunting effects between the two heavily doped regions.

3. Experimental results from DSLG cells

The voltage increase of the DSLG solar cell over the conventional BCSC will determine the potential of the DSLG solar cell. To highlight the differences between the two rear surfaces, planar front surfaces are used to minimize the recombination current introduced by the textured surfaces. The substrate resistivity is 1 Ω cm, and the wafers are about 260 μ thick. Results from these DSLG structures demonstrate that the efficiencies of these structures are higher than those from BCSC with identical substrates and thicknesses. Planar DSLG solar cells have achieved efficiencies of about 18% compared to about 17% from similar BCSCs. Currents of 35.5 mA/cm^2 on planar surfaces and 39 mA/cm^2 on textured surfaces have been measured. Both surfaces used SiO_2 as a rudimentary AR coating.

While the J_{sc} from the DSLG structure matches or slightly improves on the J_{sc} from the standard BCSCs, the increased efficiency is mainly due to the higher V_{oc}. The V_{oc} from the DSLG structure shown in Fig. 1 is 670 mV. This represents an improvement of 30 mV over the conventional BCSCs using 1 Ω cm substrates. As discussed below, the major recombination component comes from the heavily doped boron grooves. Minimization of these heavily diffused regions by replacing the grooves with wells reduces the contribution of the grooves to the total saturation current and allows for higher voltages. Open-circuit voltages of DSLG structures with heavily diffused wells rather than grooves on the rear surface have reached 685 mV with $J_{sc} = 33$ mA/cm^2, FF = 76%, and an efficiency of 17.2% (measured at UNSW). This V_{oc} represents a high voltage for a cell using only commercially compatible processes, but the FF requires further improvements to realize higher efficiencies.

4. Recombination in the DSLG solar cell

The saturation current in the DSLG cell is comprised of recombination currents due to the diffused emitter, the back surface, the grooves on the front of the cell, the bulk, the edges and the diffused rear grooves. Values for the saturation current from the front grooves, the emitter and bulk can all be estimated by comparison with other high voltage structures.

4.1. Emitter component of the saturation current

The emitter component of the total saturation current can be determined by comparison to PERL structures with identical emitters and a high V_{oc}. The V_{oc} of such planar PERL structures is 710 mV. If the V_{oc} of PERL cells is assumed to be limited by the emitter, $J_{0\text{emitter}} = 4 \times 10^{-11}$ mA/cm^2. Due to the similarity in processing and sheet resistivity of these two emitters, the emitter of the DSLG cell is assumed to contribute a maximum of 4×10^{-11} mA/cm^2 to J_0.

Charging the top surface of the PERL cells reduces the emitter contribution to J_0 and produces a 10 mV increase in V_{oc}. From this a minimum contribution from the emitter to J_0 can, therefore, be assigned to be $J_0 = 2.7 \times 10^{-11}$ mA/cm^2 in the DSLG cells.

4.2. Top groove component of the saturation current

Another component of J_0 is the recombination in the heavily diffused grooves on the front surface. The groove recombination component depends on the junction area of the heavily diffused regions, which for the grooves corresponds to the perimeter of the groove and the groove spacing. Since all the solar cells have identical groove spacings and all have very similar heavy phosphorous diffusions, the perimeter of the groove (i.e., twice the groove depth plus groove width) will determine the recombination component for the grooves. The recombination from the grooves can be accurately determined by examining the change in V_{oc} as a function of groove depth. Analysis shows that the J_0 component from the heavily diffused grooves to be 3.1×10^{-11} mA/cm^2 from grooves with a perimeter of 110 μ spaced at 1.2 mm [11]. The groove perimeter for the DSLG structure is 90 μ with identical groove spacing, giving a $J_0 = 2.5 \times 10^{-11}$ mA/cm^2.

The total top surface component to J_0 is the sum of that from the grooves and from the emitter. The minimum and maximum contributions to J_0 are $5.2 \times 10^{-11} < J_0 < 6.5 \times 10^{-11}$ mA/cm^2. This gives 701 mV > V_{oc} > 695 mV. The accuracy of these estimates can be determined by comparison to planar BCSC/PERL hybrid cells. These cells, which were primarily limited by their emitter, had identical top surfaces to the DSLG cells. Comparison of the calculated V_{oc} limits (between 695 to 701 mV) to the $V_{oc} = 693$ mV experimentally obtained on planar BCSC/PERC hybrids indicates the accuracy of these estimates.

4.3. Bulk contribution to the saturation current

The bulk contribution to J_0 depends on the lifetime in the finished cell and the cell thickness. The DSLG cells were processed on identical substrates as those used to obtain 717 mV in test structures [12], from which the bulk lifetimes were estimated to be about 1 ms. With identical substrates, similar lifetimes would be expected in the DSLG structures given the similarity in processing conditions and processing steps. In addition, the DSLG structure allows the possibility of gettering at the rear surface, further supporting high lifetimes in the base. Assuming a base lifetime of 1 ms, a resistivity of 1 Ω cm, and a thickness of 260 μ, the J_0 from the base is 2×10^{-11} mA/cm^2.

4.4. Back surface contribution to the saturation current

The back surface uses a floating junction for passivation. Since this junction is identical to the front junction, the maximum J_0 component that the back could contribute would be equal to that from the front junction. However, since the rear junction is floating rather than contacted, the actual contribution is expected to be much less, so the maximum $J_{0\mathrm{back}} = 4 \times 10^{-11}$ mA/cm^2. Together the rear surface and bulk contribute between 1×10^{-11} (assuming very good rear passivation) and 4×10^{-11} mA/cm^2. An additional estimate of the combined bulk and rear surface contribution can be calculated by treating the cell as a transistor structure with the collector floating [9]. These calculations give the rear surface contribution to J_0 as 3×10^{-11} mA/cm^2, which is within the previously calculated range.

Table 1
Recombination mechanisms and their effect on V_{oc} (the upper and lower bounds refer to the upper and lower bounds on the recombination current from that region; the limiting V_{oc} represents the range of open-circuit voltages possible from all of the previous components)

Region of recombination	Lower bound (mA/cm^2)	Upper bound (mA/cm^2)	Limiting Voc (mV)	Limits determined by
Emitter and surface	2.7×10^{-11}	4×10^{-11}	717–720	Comparison to PERL
Groove diffusion	2.8×10^{-11}	2.8×10^{-11}	696–701	Measurement of variation in V_{oc}
Bulk contribution	2×10^{-11}	2×10^{-11}	689–693	Comparison to PERL
Floating junction	1×10^{-11}	4×10^{-11}	680–690	Modelling
Total (no rear grooves)	8.5×10^{-11}	1.3×10^{-10}	680–690	

4.5. Boron groove diffusion component of the saturation current

Without the effect of the rear grooves the total calculated J_0 is between 8.5×10^{-11} mA/cm^2 and 1.3×10^{-10} mA/cm^2. An intermediate value of $J_0 = 9.5\times10^{-11}$ mA/cm^2 is used to determine the contribution from the rear grooves. This intermediate value assumes that the rear surface is well passivated. The difference between these calculated values of J_0 and those measured can be attributed to the recombination in the boron diffusion and depletion region surrounding the groove. The reverse saturation current from the 671 mV DSLG cell is calculated as 1.8×10^{-10} mA/cm^2, about twice the value of $J_0 = 9.5\times10^{-11}$ above. This extra recombination current is attributed to the recombination in the rear grooves. Edge effects are neglected since DSLG cells with an area of 4 cm^2 have $V_{oc} = 669$ mV, similar to $V_{oc} = 671$ mV for larger area cells of 11.5 cm^2.

The above analysis prompted the development of the new DSLG structure in which the rear grooves are replaced by wells. This structure achieved a much higher V_{oc} of 685 mV by eliminating over 90% of the heavily boron doped volume. The reduction in the heavily doped region reduces the recombination current component from the rear grooves. In the 685 mV cell, the voltage is no longer limited by the recombination in the grooves. The measured V_{oc} lies within the calculated range of Voc for the DSLG structure as in Table 1.

5. Conclusions

The DSLG solar cell allows for a 30 mV increase over a similar BCSC with similar material parameters. The rear floating junction passivates the rear surface. The dominant recombination mechanism from these DSLG solar cells is the recombination in the rear grooves, which account for up to half of the total saturation current. The contribution of the rear boron grooves is higher than the contributions from the front grooves possibly due to the beneficial gettering effects in the phosphorous grooves. Reducing the area of the heavily diffused boron region by replacing the grooves with wells allows for a V_{oc} of 685 mV an increase of 45 mV over similar BCSC. This is the highest voltage for a silicon solar cell using only commercially proven processing steps. Further improvements to the standard DSLG structure can be realized by improving the FF and by reducing the contribution of the groove diffusion by either lowering the groove diffusion or by reducing the size of heavily diffused regions.

Acknowledgements

The contributions of Jianhua Zhao, Aihua Wang, Fuzu Zhang, Seyed Ghozati, Wu Yan, Ru-Dong Xiao and other members of the Centre for Photovoltaic Devices and Systems are acknowledged. This work has been directly supported by the Australian Research Council, the Energy Research and Development Corporation, the New South Wales Office of Energy and Sandia National Laboratories. The Centre for Photovoltaic Devices and Systems is supported by the Australian Research Council and Pacific Power.

References

[1] N.B. Mason and D. Jordan, A high efficiency silicon solar cell production technology, Conf. Record, 10th EC Photovoltaic Solar Energy Conf., Lisbon, 1991, p. 280.
[2] H.W. Boller and W. Ebner, Conf. Record, 9th EC Photovoltaic Solar Energy Conf., Freiburg, 1989.
[3] J.H. Wohlgemuth and S. Narayanan, Buried contact concentrator solar cells, Conf. Record, 22nd IEEE Photovoltaic Specialists Conf., Las Vegas, 1991, p. 273.
[4] S.R. Wenham, Y. Wu, R.D. Xiao, M. Taouk, M. Guelden, M.A. Green and D. Hogg, Pilot production of laser grooved silicon solar cells, Conf. Record, 11th EC Photovoltaic Solar Energy Conference, Montreux, 1992, p. 416–419.
[5] S. Wenham, Buried Contact Silicon Solar Cells, Prog. in Photovoltaics 1 (1993) 3–10.
[6] M.A. Green, S.R. Wenham, J. Zhao, A. Wang, X. Dai, A. Milne, M. Taouk, J. Shi, F. Yung, A.B. Sproul and A. Stevens, One-sun silicon solar cell research, Report SAND66-5863, Sandia National Laboratories, 1992.
[7] S.R. Wenham, C.B. Honsberg and M.A. Green, Buried contact silicon solar cells, 7th Int. Photovoltaic Science and Engineering Conf., Nagoya.
[8] M. Ghannam, E. Demesmaeker, J. Nijs, R. Mertens and R. Van Overstraeten, Two dimensional study of alternative back surface passivation methods for high efficiency solar cells, Conf. Record, 11th EC Photovoltaic Solar Energy Conference, Montreux, 1992, p. 45–48.
[9] M. Ghannam, A new n^+-p-n^+ structure with back side floating junction for high efficiency silicon solar cell, Conf. Record, 22nd IEEE Photovoltaic Specialists Conf., Las Vegas, 1991, p. 284.
[10] R.A. Sinton, and R.M. Swanson, Simplified backside-contact solar cells, IEEE Trans. Electr. Dev. 37(2) (1990) 348–352.
[11] C.B. Honsberg and S.R. Wenham, New insights gained through pilot production of high efficiency silicon solar cells, submitted to Progress in Photovoltaics.
[12] A. Wang, J. Zhao, A.G. Aberle, S.R. Wenham and M.A. Green, 717 mV Open-circuit voltage silicon solar cells using hole-capture limited surface passivation, Proc. 11th Photovoltaic Solar Energy Conference, Montreux, 1992.