J. Korean Inst. Electr. Electron. Mater. Eng.
Vol. 35, No. 6, pp. 616-621 November 2022
DOI: https://doi.org/10.4313/JKEM.2022.35.6.11
ISSN 1226-7945(Print), 2288-3258(Online)

Regular Paper

Design Optimization of the Front Side in n-Type TOPCon Solar Cell

Sungjin Jeong[1], Hongrae Kim[1], Sungheon Kim[2],
Suresh Kumar Dhungel[3], Youngkuk Kim[3], and Junsin Yi[3]

[1] Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon 16419, Korea
[2] Interdisciplinary Program in Photovoltaic System Engineering, Sungkyunkwan University, Suwon 16419, Korea
[3] College of Information and Communication Engineering, Sungkyunkwan University, Suwon 16419, Korea

(Received September 1, 2022; Revised September 8, 2022; Accepted September 8, 2022)

Abstract: Numerical simulation is a good way to predict the conversion efficiency of solar cells without a direct experimentation and to achieve low cost and high efficiency through optimizing each step of solar cell fabrication. TOPCon industrial solar cells fabricated with n-type silicon wafers on a larger area have achieved a higher efficiency than p-type TOPCon solar cells. Electrical and optical losses of the front surface are the main factors limiting the efficiency of the solar cell. In this work, an optimization of boron-doped emitter surface and front electrodes through numerical simulation using “Griddler” is reported. Through the analysis of the results of simulation, it was confirmed that the emitter sheet resistance of 150 Ω/sq along the front electrodes having a finger width of 20 μm, and the number of finger lines ~130 for silicon wafer of M6 size is an optimized technology for the front emitter surface of the n-type TOPCon solar cells that can be developed.

Keywords: TOPCon solar cell, Simulation, Griddler, Doping, Electrode

1. INTRODUCTION

Solar photovoltaic systems one of most effective sustainable energy sources of the world. Solar cells are the backbone of photovoltaic (PV) systems. Silicon based photovoltaic systems still cover more than 90% of the global PV market. Currently competing designs of silicon solar cells are Passivated Emitter Rear Contact (PERC), Interdigitated Back Contact (IBC), Heterojunction (HJT) and Tunnel Oxide Passivated Contact (TOPCon) [1-3]. In recent years, n-type TOPCon solar cells are increasing their share in global market. The n-type TOPCon solar cells with large area with an open-circuit voltage (V_{OC}) of 721 mV and conversion efficiency of 25.3% have already been fabricated elsewhere [4].

Compared to the n-type wafer, the p-type wafer has a lower tolerance to impurities, so there is a limit for efficiency improvement in case of large-area industrial solar cells. Since the n-type wafer has excellent resistance to impurities present, the minority carrier lifetime is relatively longer. There is minimal Light-Induced Degradation (LID) in n-type wafers due to which higher conversion

✉ Junsin Yi; junsin@skku.edu

efficiency of the solar cell can be achieved by starting with n-type silicon wafers compared to p-type wafers [5].

TOPCon solar cell is composed of polysilicon layer and a very thin oxide film on the back side, and the tunneling effect enables selective collection of electrons, thereby increasing the efficiency by preventing recombination of photogenerated carriers. For this reason, the power generation of TOPCon solar cells has been mainly concentrated on the rear part. However, the structural improvement of the rear side is optimized to a large extent, and there is still need for research to reduce the power loss on the front side [6,7].

The solar cell emitter should be designed to minimize both electrical and optical losses. Resistive loss through the metal contact of the front part of the solar cell and the recombination loss on the surface are the main factors limiting the efficiency of the solar cell [8,9]. Before 2000, solar cells having emitters with low sheet resistance of 40~50 Ω/sq were fabricated with heavy doping to reduce contact resistance. However, the reduction of the sheet resistance lowers the quantum efficiency in the short wavelength region of solar spectrum, and it results in the reduced short-circuit current (I_{SC}) and V_{OC}, which ultimately reduces conversion efficiency of the solar cells.

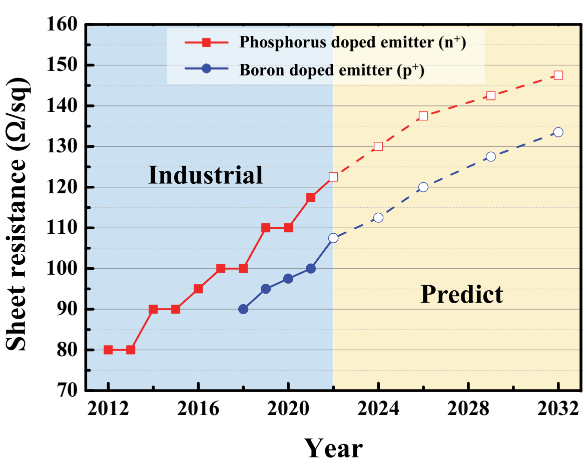

Fig. 1. Trend of increase in emitter sheet resistance of solar cell in recent years and that projected for near future by ITRPV [11-20].

Since mid-2000s, the trend of using emitters with high sheet resistance in the range of 80-100 Ω/sq has gained momentum [10]. Figure 1 shows the recent trend of increasing emitter sheet resistance of solar cells for better performance as reported in different volumes of International Technology Roadmap for Photovoltaics (ITRPV) published over the period of 10 years [11-20].

Afterwards, as the selective emitter began to attract attention as a method of reducing recombination and resistive losses of the front surface of the solar cells, light doping was performed in the area other than that covered by front electrode, thereby forming a high surface resistance region of 200 Ω/sq or even more. However, in the case of a selective emitter, many basic technologies are required to have competitiveness in the mass production process due to an increase in process steps and costs, whereas in the case of an n-type wafer, it is difficult to form a selective emitter because technology has not been developed yet. For this reason, studies for reducing the finger width of the electrode formed on the front surface are being conducted to reduce the losses along with the increase in the sheet resistance of a homogeneous emitter.

The emitter acts as a path to move the charge carrier generated by the light incident on the surface, and the charge carriers are collected through the electrodes. When the sheet resistance of the emitter increases, the movement of charge carriers becomes difficult and the gap between the electrodes must be reduced for smooth collection of charge carriers. If the distance between electrodes is reduced while the line width is greater, the front shading area increase and the light absorbing surface of silicon decrease, causing increased shading (optical) loss. In addition, if the finger width is reduced and the number of busbars increased in proportion, it thereby reduces power loss and ultimately increase cell efficiency [21].

Figure 2 shows the trend of changes in finger width of screen-printed electrodes based on research papers published over the past decade

[22,23]. In around 2010, electrodes with finger width between 80 μm and 100 μm were screen-printed, but it was gradually decreased. By the end of 2020, the width of the screen-printed finger was less than 20 μm, which is just about a quarter of the width that was screen-printed about a decade age.

This study aims to analyze the emitter and electrode characteristics applicable to the n-type TOPCon solar cell by using. Griddler simulation, and to suggest optimal and conductive conditions for industrial high efficiency n-type TOPCon silicon solar cell fabrication.

2. EXPERIMENTAL

In this study, simulation-based investigation on boron doped emitter and the cell characteristics according to the electrode pattern were analyzed. The simulation software used was Griddler 2.5 pro. Griddler is a simulation that can analyze the characteristics of a solar cell using geometric definitions for the metallization of the front and back sides of the solar cell [24]. Based on the TOPCon structure for the study, n-type silicon wafer of size M6 (166 mm × 166 mm) with a thickness of 180 μm and resistivity of 1 Ω-cm was considered. The front surface considered for simulation was textured, whereas the back surface was polished, and the Gaussian function was chosen as the doping profile function at a peak position of 0.15 μm and depth factor of 0.2 μm. The corresponding results were obtained by varying the sheet resistance from 50 Ω/sq to 250 Ω/sq. In the case of the metallization for electrode formation, both the surfaces were screen-printed grid type for a bifacial structure. The number of front and rear busbars was 9 and solder/probe point kept fixed at 12. The busbar width was set to 60 μm for front surface and 165 μm for rear surface. For the rear electrode, the finger width was fixed to 100 μm and the number of fingers was fixed as 110, and those parameters for front electrode were varied.

3. RESULTS & DISCUSSION

The Internal Quantum Efficiency (IQE) is an important parameter to see how effectively the energy of photons incident on the solar cell can be utilized to generate photocurrent. Figure 3 shows the variation in IQE with wavelength of the solar spectrum. The variation of IQE in the range from 300 nm to 750 nm for boron doped emitter with different sheet resistance from 50 Ω/sq to 250 Ω/sq

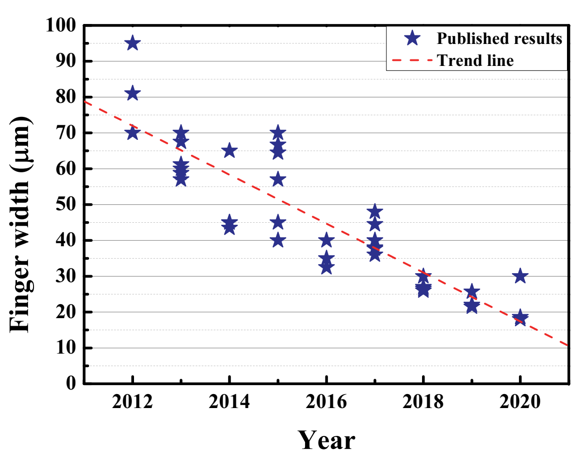

Fig. 2. Trend of decrease in finger width as reported elsewhere in the past decade [22,23].

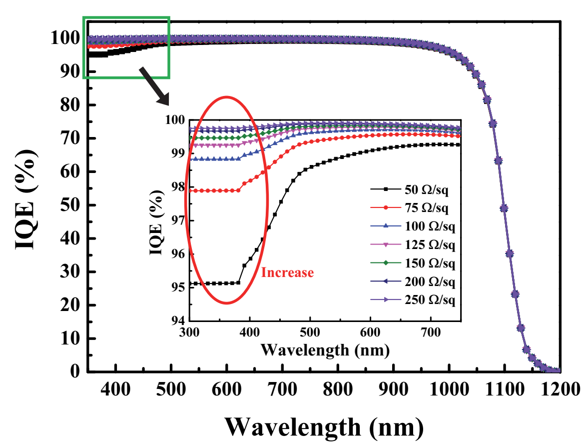

Fig. 3. Variation of IQE with wavelength of the solar spectrum, especially from 300 nm to 750 nm range (blow-up image) for various sheet resistances of boron doped emitter for n-type TOPCon solar cells.

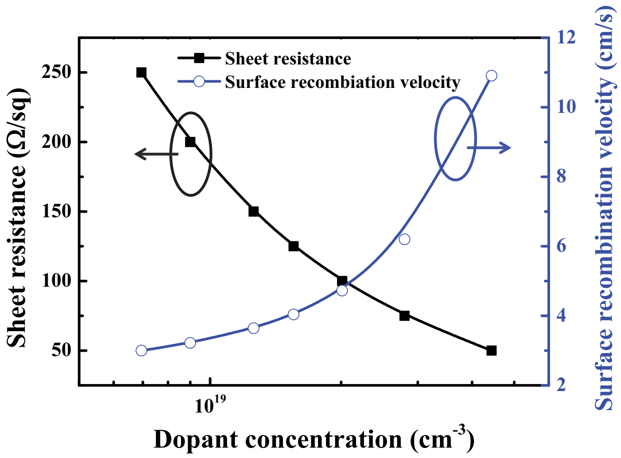

Fig. 4. Variation in sheet resistance and surface recombination velocity with dopant concentration in boron doped emitter surface.

has been magnified in the inner blow-up image.

It is obvious from the Fig. 3 that the sheet resistance of the emitter has significant impact in the relatively shorter wavelength range that represents ultraviolet and visible spectrum, compared to the longer wavelength region of solar spectrum.

Quantum efficiency in the shorter wavelength region (300 nm to 750 nm) is greatly affected by surface recombination. In the case of low sheet resistance, the dopant concentration in emitter surface is relatively higher, and hence the surface recombination velocity is also high. The lower sheet resistance decrease the mobility of carriers and hence increases recombination, thereby reducing the IQE in the shorter wavelength region. Therefore, an emitter with higher sheet resistance is required to improve quantum efficiency in the shorter wavelength region of the solar spectrum [25,26].

The sheet resistance was varied from 50 Ω/sq to 250 Ω/sq, and the corresponding values of performance parameters of solar cell such as V_{OC}, short circuit current density (J_{SC}), fill factor (FF), and conversion efficiency (η) thus obtained after simulation were plotted for comparative analysis, as shown in Fig. 5. It is obvious from the figure that the highest conversion efficiency was achieved for the front emitter of sheet resistance 150 Ω/sq.

When an emitter with higher sheet resistance is formed, on the one hand, the gap between fingers should be made narrower to avoid additional resistive loss, which results in the increase in number of finger lines in the front surface. However, it reduces permissible front surface area of solar cell to absorb incident light, which ultimately increases shading or optical loss. Therefore, on the other hand, to reduce the optical loss, the finger width needs to be reduced. Hence, a reasonable trade-off between optical and resistive loss on the front emitter surface must be achieved for the optimal conversion efficiency of solar cells.

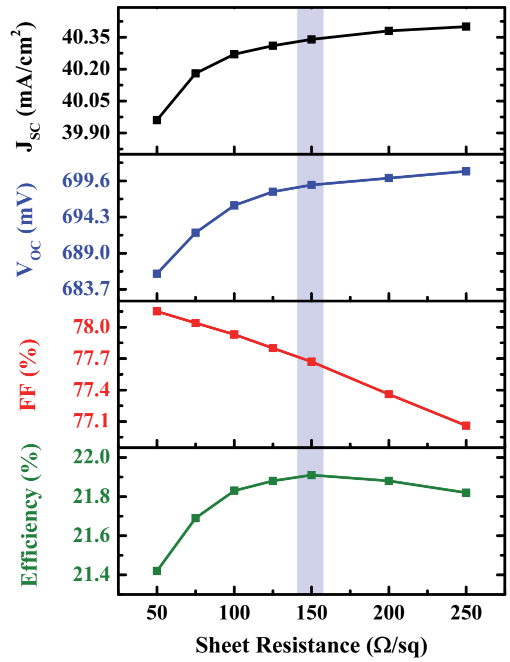

Fig. 5. Variation in performance parameters of solar cells with sheet resistance of boron doped front emitter surfaces, as obtained by simulation.

Figure 6 show the optimization of the finger width and number of finger lines in the boron doped emitter for already optimized sheet resistance of 150 Ω/sq, as shown in Fig. 5. In Fig. 6(a), for a particular shading loss, smaller the line width, greater the number of finger line needed. From the Fig. 6(b), it is seen that the efficiency of 21.6% or more can be obtained when the finger width is less than ~20 μm and the number of finger lines is 130 or more.

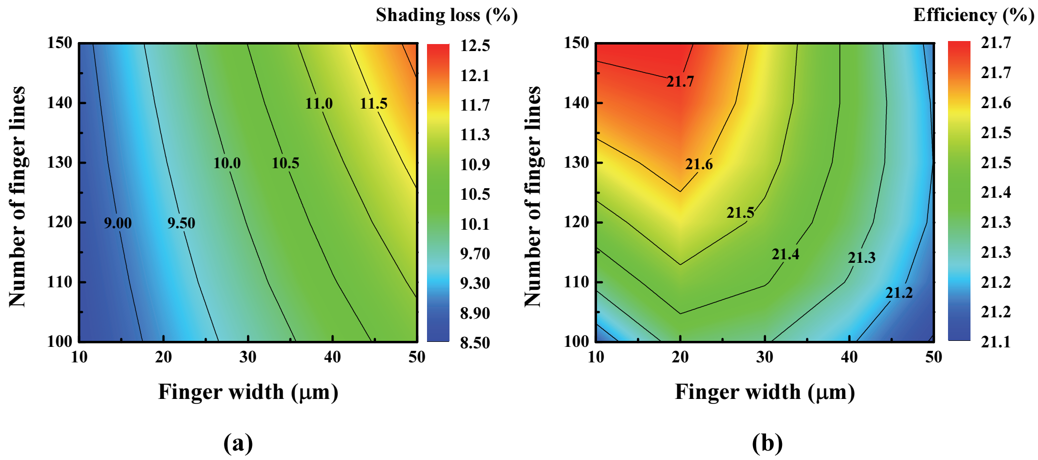

Fig. 6. Contour analysis on variation of finger width and number of finger lines along with resulting (a) shading loss, and (b) conversion efficiency in a solar cell.

4. CONCLUSION

The transition from p-type wafers to n-type silicon wafers for TOPCon solar cells is accelerating, and for this purposes, it is necessary to improve conversion efficiency of solar cells by optimizing the emitter sheet resistance and electrodes pattern with a trade-off between optical and electrical losses. In this paper, optimization of the boron doped emitter and front electrode on the emitter surface of the n-type TOPCon solar cell is reported through the analysis of data obtained by Griddler simulation. For the boron doped front emitter of n-type TOPCon solar cell, sheet resistance of 150 Ω/sq was found to be best condition for highest conversion efficiency for which optimized finger width of 20 μm and the number of finger lines ~130 are required. The results obtain through this investigation can be implemented for the industrial production of high efficiency TOPCon solar cell fabricated with n-type silicon wafer. With further improvement in the quality of bulk silicon and optimization of rear surface of the TOPCon solar cells during fabrication starting with n-type silicon wafers, higher conversion efficiency can be materialized.

ORCID

Junsin Yi https://orcid.org/0000-0002-6196-0035

ACKNOWLEDGEMENTS

This work was supported by the Technology Innovation Program (or Industrial Strategic Technology Development Program) (20016058) funded By the Ministry of Trade, Industry & Energy(MOTIE, Korea) and the SungKyunKwan University and the BK21 FOUR(Graduate School Innovation) funded by the Ministry of Education (MOE, Korea) and National Research Foundation of Korea(NRF).

REFERENCES

[1] G. M. Wilson, M. Al-Jassim, W. K. Metzger, S. W. Glunz, P. Verlinden, G. Xiong, L. M. Mansfield, B. J. Stanbery, K. Zhu, Y. Yan, J. J. Berry, A. J. Ptak, F. Dimroth, B. M. Kayes, A. C. Tamboli, R. Peibst, K. Catchpole, M. O. Reese, C. S. Klinga, P. Denholm, M. Morjaria, M. G. Deceglie, J. M. Freeman, M. A. Mikofski, D. C. Jordan, G. TamizhMani, and D. B. Sulas-Kern, *J. Phys. D: Appl. Phys.*, **53**, 493001 (2020). [DOI: https://doi.org/10.1088/1361-6463/ab9c6a]

[2] A. Richter, J. Benick, F. Feldmann, A. Fell, M. Hermle, and S. W. Glunz, *Sol. Energy Mater. Sol. Cells*, **173**, 96 (2017). [DOI: https://doi.org/10.1016/j.solmat.2017.05.042]

[3] J. Liu, Y. Yao, S. Xiao, and X. Gu, *J. Phys. D: Appl. Phys.*, **51**, 123001 (2018). [DOI: https://doi.org/10.1088/1361-6463/aaac6d]

[4] M. A. Green, E. D. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, K. Bothe, D. Hinken, M. Rauer, and X. Hao, *Progress in Photovoltaics: Research and Applications*, **30**, 687 (2022). [DOI: https://doi.org/10.1002/pip.3595]

[5] B. Pal, S. Ray, U. Gangopadhyay, and P. P. Ray, *Materials Research Express*, **6**, 075523 (2019). [DOI: https://doi.org/10.1088/2053-1591/ab18ee]

[6] Y. Zhou, K. Tao, A. Liu, R. Jia, S. Jiang, J. Bao, S. Yang, Y. Cao, and H. Qu, *Appl. Phys. A*, **126**, 671 (2020). [DOI: https://doi.org/10.1007/s00339-020-03851-5]

[7] Q. Wang, W. Wu, N. Yuan, Y. Li, Y. Zhang, and J. Ding, *Sol. Energy Mater. Sol. Cells*, **208** 110423 (2020). [DOI: https://doi.org/10.1016/j.solmat.2020.110423]

[8] Y. Tao, K. Madani, E. Cho, B. Rounsaville, V. Upadhyaya, and A. Rohatgi, *Appl. Phys. Lett.*, **110**, 021101 (2017). [DOI: https://doi.org/10.1063/1.4973626]

[9] P. Ebrahimi, M. Kolahdouz, M. Norouzi, H. Aghababa, A. Aletayeb, and E. Asl-Soleimani, *J. Mater. Sci.: Mater. Electron.*, **28**, 10794 (2017). [DOI: https://doi.org/10.1007/s10854-017-6856-z]

[10] H. Nishimura, M. Manabe, H. Sakagawa, and T. Fuyuki, *Jpn. J. Appl. Phys.*, **54**, 066502 (2015). [DOI: https://doi.org/10.7567/JJAP.54.066502]

[11] A. Metz, G. Demenik, and A. Richter, (2013). *International Technology Roadmap for Photovoltaic (ITRPV)*, 4th edn. (Berlin, Germany, 2013).

[12] ITRPV 2014. International Technology Roadmap for Photovoltaic (ITRPV) Fifth Edition—2013 Results; ITRPV: Frankfurt, Germany, 2014.

[13] ITRPV 2015. International Technology Roadmap for Photovoltaic (ITRPV) Sixth Edition—2014 Results; ITRPV: Frankfurt, Germany, 2015.

[14] ITRPV 2016. International Technology Roadmap for Photovoltaic (ITRPV) Seventh Edition—2015 Results; ITRPV: Frankfurt, Germany, 2016.

[15] ITRPV 2017. International Technology Roadmap for Photovoltaic (ITRPV) Eighth Edition—2016 Results; ITRPV: Frankfurt, Germany, 2017.

[16] ITRPV 2018. International Technology Roadmap for Photovoltaic (ITRPV) Ninth Edition—2017 Results; ITRPV: Frankfurt, Germany, 2018.

[17] ITRPV 2019. International Technology Roadmap for Photovoltaic (ITRPV) Tenth Edition—2018 Results; ITRPV: Frankfurt, Germany, 2019.

[18] ITRPV 2020. International Technology Roadmap for Photovoltaic (ITRPV) Eleventh Edition—2019 Results; ITRPV: Frankfurt, Germany, 2020.

[19] ITRPV 2021. International Technology Roadmap for Photovoltaic (ITRPV) Twelfth Edition—2020 Results; ITRPV: Frankfurt, Germany, 2021.

[20] ITRPV 2022. International Technology Roadmap for Photovoltaic (ITRPV) Thirteenth Edition—2021 Results; ITRPV: Frankfurt, Germany, 2022.

[21] S.-B. Jo, H.-S. Kim, and J.-Y. Heo, *Korea Photovoltaic Society*, **1**, 15 (2015).

[22] A. Lorenz, M. Linse, H. Frintrup, M. Jeitler, A. Mette, M. Lehner, R. Greutmann, H. Brocker, M. König, D. Erath, and F. Clement, *35th European Photovoltaic Solar Energy Conference and Exhibition*, **4**, 819 (2018). [DOI: https://doi.org/10.4229/35thEUPVSEC20182018-2DV.3.65]

[23] T. Wenzel, A. Lorenz, E. Lohmüller, S. Auerbach, K. Masuri, Y. C. Lau, S. Tepner, and F. Clement, *Sol. Energy Mater. Sol. Cells*, **244**, 111804 (2022). [DOI: https://doi.org/10.1016/j.solmat.2022.111804]

[24] J. Wong, P. Teena, and D. Inns, *2017 IEEE 44th Photovoltaic Specialist Conference (PVSC)*, (IEEE, 2017) pp. 3113-3118. [DOI: https://doi.org/10.1109/PVSC.2017.8366135]

[25] A. Cuevas, *Energy Procedia*, **55**, 53 (2014). [DOI: https://doi.org/10.1016/j.egypro.2014.08.073]

[26] Y. Zhang, L. Wang, D. Chen, M. Kim, and B. Hallam, *J. Phys. D: Appl. Phys.*, **54**, 214003 (2021). [DOI: https://doi.org/10.1088/1361-6463/abe900]