International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 10 Issue 1 ǁ 2022 ǁ PP. 73-79

A Review on Electrical Characteristics of Bifacial PERC Solar Cell

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Abstract
Bifacial PERC (PERC+) solar cell has achieved greater success due to its properties. P-type PERC+ is fabricated by Al finger grid rather than full area Al layer on the rear side as compared to Aluminum back surface Field (Al-BSF) solar cell. In last few years, research efforts have been devoted to bifacial PERC mostly based on p-type substrate to make it more efficient. N-type PERC+ has high efficiency but cost is higher due to use of silver (Ag) paste on both sides. In particular, 22.3-22.5% efficiency has been achieved which is almost highest efficiency for p-type Bifacial PERC. Photovoltaic (PV) silicon solar has electrical performance is defined through its (I-V) parameters, which are determined by device and material properties. In this paper, a brief historical review on electrical characteristics of bifacial PERC is presented. When industrialization technology is constantly improving, e.g., emitter doping optimization, rear thickness changes, laser doped selective emitter, shading losses on rear side etc. and their effect on electrical parameters (V_{oc} , I_{sc} , FF, η) *discussed in detail.*

Keywords: *BiPERC, Al-BSF, efficiency, selective emitter*

Date of Submission: 10-01-2022 Date of acceptance: 24-01-2022

I. INTRODUCTION

First PERC (Passivated Emitted and Rear Cell) structure was developed in lab scale by the University of New South Wales in 1989 [1]. PERC is a new technology that adds a dielectric passivation layer on the back of the cell to improve conversion efficiency. A silicon dioxide layer has been added to back surface of cell to replace full area Aluminum Back Surface Field (Al-BSF), which minimizing the recombination of charge carrier at the rear surface and internal reflectivity increases and more infrared light absorption. [2]. PERC has already proven to be theoretically and experimentally high efficiency solar cell technology [3]. In last few years, more and more solar cell companies and researchers have started research on bifacial PERC solar cells and their production making it a conventional high-efficiency cell technology.

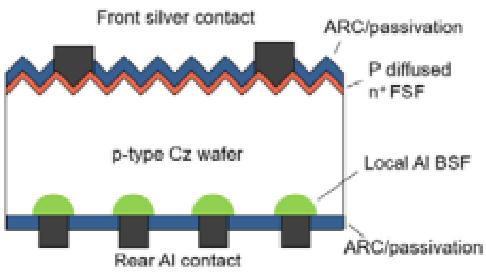

Figure 1: Bifacial PERC solar cell

Bifacial solar cell concept has first been published in 1960 by H. Mori [4]. PN-junction idea was used on the front and rear sides of the cell to improve the storage of charge carriers on both surfaces of the wafer. Bifacial PERC provide additional benefits by absorbing incident irradiation from both the back and the front sides (i) reduced in cell working temperature due to increase open-circuit voltage (ii) decreased parasitic absorption to reduce losses and increased recombination on the Al Back Surface (BSF) field interface [6]. The temperature of the cell can be reduced due to absence of metallization at rear surface. As a result, the bifacial PV cell work at a lower temperature and increased power output than monofacial cells [7,32].

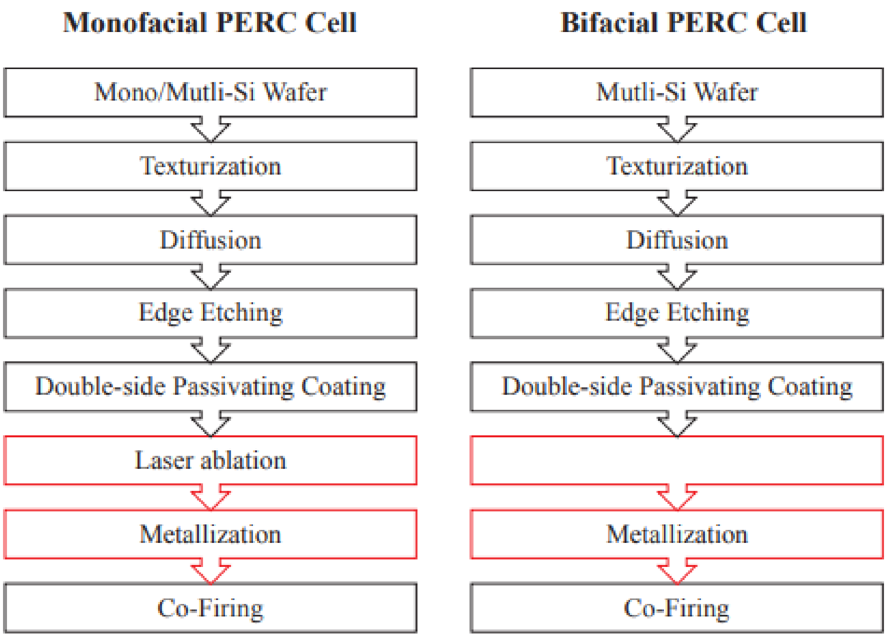

Figure 2: Relative comparison of the process flow of monofacial vs bifacial

PERC cell could have bifacial structure by exchanging the full area Al layer with Al finger grid on rear side Fig. 1[5,40]. PERC Cell compared with a full Al layer, but bifacial cell is unique because both surfaces add dielectric layer, metallic finger grids, less mechanical stress in wafers. The Al finger grids and antireflective coating (ARC) film at the rear [9] can enhance the rear power generation with maintaining front side efficiency of the bifacial PERC cell. The ARC film can absorb more light and finger should attain highly conductive back contact with low shading. [3]. Hence its efficiency can be increased in comparison to that of industrial PERC. In 2015, first PERC+ solar cell was published. With an industrial p-type Czochralski-grown silicon (Cz-Si) with five busbar PERC, Solar world achieved a record efficiency of 21.67% verified by the Fraunhofer ISE CalLab in Germany.

Solar cell's electrical parameters are defined by its (I-V) characteristics. So, I-V properties are determined by different parameters including V_{oc},I_{sc}, diode ideality photo induced current, diode saturation current and parasitic resistance. All the parameters depend on the configuration of solar cell, operating conditions and its material properties. The investigation of I-V properties at standard test conditions allows for finding the additional electrical performance parameters as well as the identification of parasitic resistances [8]. In 2015, T. Dullweber et al. [9] studied the electrical characteristics of bi-PERC cell with rear Al fingers grid. The Al fingers can increase the open-circuit voltage of the bifacial PERC than monofacial PERC. Bifacial PERC cell has a lower FF and 0.1cm^2 higher series resistance R_s as compared to monofacial PERC.

II. BRIEF HISTORICAL OVERVIEW OF BIFACIAL PERC

2.1 Introductory work:

In an industrial PERC cell, screen printed Al layer used on rear side of p-type wafers that contacts the silicon of p-type wafers where the passivation layer removed by (LCO) laser contact opening. Blaker et al. [1] used a full area Al rear contact on PERC cell in 1989. This cell stops any transmission of light from sun due to huge amount of Al paste on rear side. So, Al grid fingers are applying in bifacial PERC cell at the rear side. Use full Al layer on the rear side the conductivity of solar cell was reduce. Dullweber et al. proposed the bifacial PERC structure in 2015. According to Dullweber, bifacial PERC structure advantages are a little amount of necessary metal, open-circuit voltage improved and the ability to use absorb more light on both sides. Most significant advantages of Bifacial PERC construction is that it may be used with light responses from both sides, hence increasing light absorption and possibly increasing short-circuit current density [9].

K. KrauB et al. analyzed the numerical simulation results for bifacial PERC solar cell that illustrate bifacial achievements for different properties of metallization at rear side in term of conductivity and experimental results show with Screen-Printed Al grids at back side. Losses were expected because series resistance increase when the whole area of metallization is converted to rear side, the Al grids is compensated more by the bifacial gains due to the intensity of light, according to numerical device simulations of bifacial PERC concept. Bifacial PERC cells have higher series resistance losses due to carrier transport on bulk, because rear contacts pitch is greater than that of PERC cells [10]. For building-integrated photovoltaics (BIPV), Binhui and Yifeng et al. [11] proposed a newly developed colored module. That is, the module's front sides remain dark blue while their back sides become colorful. They vary the back side colors of cell and showed that performance of rear-colored Bifacial P-type PERC cell with different rear side thickness. They successfully achieved cell whose rear was colored blue, yellow, red and green. The yellow, red and green cell show similar electrical properties of standard p-PERC, which was installed in one module without I_{sc} mismatch. The blue cell has a lower open circuit V_{oc} and efficiency, probably due to poor passivation at rear side.

In 2016 C. kranz et al. find out the different effects of LCO linewidths on performance of PERC and PERC+ cell and examine the physical cause of various Al-BSF depths from the Al fingers. Designed Al-fingers grid on rear side in such technique that minimized the losses of series resistance through Al fingers. Another problem with PERC+ is accurate arrangement of Al finger-print on top of LCO. They have been used different LCO linewidths for both types of cells, while keep the pitch is constant for each. Average PERC efficiencies range from 20.7% to 21.1% for contact widths 68m to 110μm, with inclination to lower efficiencies for narrow contacts. On the other hand, increase the efficiency of PERC+ from 20.4 to 20.6% with reduced the width of back contact [9]. V_{oc} of the PERC+ increase by 5mV due to lower metallization fraction of the back surface [3].

S.Yu Chen, H. Chang et al. [12] examined the P-type four-busbars bifacial solar cell with lifetime variation and external quantum efficiency for different rear passivated stack layers. The results reveal that annealing temperature has consequential effect on passivation layer. Thicker Al_2O_3 layer anneal at 600°C shows higher lifetime. External quantum efficiency is higher in different stack layers. Isc and Voc increase as surface recombination reduced.

T. Dullweber et al and H. Schulte-Huxel et al. published a prototype PERC+ module with using Smart Wire Connection Technology (SWCT). Connected 18 PERC+ solar cell to the Ag front and Al fingers with 18 wires instead of utilizing Ag busbar or Ag pads. These wires are cover with InSn as low temperature. Due to these InSn-coated wires, enhance UV transformation and reduce optical losses. The prototype modules produced have independently verified the efficiencies of front and back side are 19.8% and 16.4% respectively. These values are equal to bifacial efficiency of 21.4%, which is more than 1% higher than the previous world record mono facial PERC module efficiency. The PERC+ prototype cell obtains the highest Isc due to missing busbars shadowing [13].

W. Wu, Z. Zhang et al. investigated the contract between a highly and lightly doped emitter region under the metal fingers, which was significant challenge [14,29]. This challenge has tried to remove by the Selective-Emitter (SE) contact structure at crystalline silicon [15,16]. The laser doped Selective-Emitter was used for P-type PERC+ [17,18]. They were optimized that R_{sh} (sheet resistance) of lightly and highly doped emitter is prepared through laser-doped process. Series resistance was minimized by use a Double-Screen-Printed Al fingers and produce a greater output of electrical power density. In Double-Screen-Printed (DP), printed Al-electrode to obtain highest characteristic ratio of Al fingers and reduce grid resistance. When the R_{sh} of highly doped SE area is increased, lightly doped emitter junction depth is decreases, so lowering the surface recombination velocity as well as Auger and Shockly-Read-Hall (SRH) recombination [19]. Efficiency and output power density of Bifacial PERC solar cells can be enhanced by Laser Selective Emitter and Double Screen Printed electrode on rear. DP PERC+ solar cell of the front side efficiency was 22% bifaciality factor 70% with optimized R_{sh} of highly doped Selective-Emitter with 700Ω⁄(sq) [20].

N Boukortt et al. used SILVACO TCAD in 2018 to study the impact of contact resistance, output characteristics of temperature dependence, and achieving an efficiency 26.79% of n-type bi-PERC solar cell. In the temperature range 25 to 100°C, the temperature dependence of performing parameters I_{sc}= 43.93mA/cm^2, V_{oc}=763mV, FF= 80.44%, P_{max}=269.77W⁄m^{-2} was explored. The material band gap, V_{oc}, fill factor and P_{max} all decreases as temperature increases. These results are controlled by V_{oc}, increase in I_{sc} with temperature does not contribute to FF [21,22]. As a result, the two-dimensional simulation results show that tendency of V_{oc}decreases and efficiency reduces with increasing temperature in the solar cell [23].

2.2 Recent Developments in Bifacial PERC:

During 2019 to 2021, the silicon PV industry have significant changes, including reduce manufacturing cost and a continued increased in efficiency and module power.*Dangping Hu et al.* was optimized the rear structure by changing the Al finger grid width and silicon nitride film thickness on rear side. When increases the finger width Although the electrical performance and front side External Quantum efficiency (EQE) has small changes and thickness of rear SiN_Y film decreases. When thickness of rear SiN_Y film decreases from 140nm to 190nm, the apparent colour change from golden yellow to dark blue, which improves absorption of light. However, due to low reflectance of $SiN_Y$with 90nm, the I-V parameter for the rear side was change as well, I_{sc} is increased from $6.772A$ to $7.208A$, resulting maximum efficiency 15.66% of rear side. The PERC+ solar cell attains the best efficiencies E(front) 21.24%, E(rear) 15.66% and bifaciality factor 74% by optimizing rear structure. I_{sc} and efficiency decreases as width of Al finger grid increases because the total area of metallization fraction of Al finger grid increases from 14.75% to 24.35%[24].

Bifacial PERC cell which rear side was semi-planarized with efficiency of 21.2% [25].The cell consists of five busbars with 500μm width, a 40μm large Ag fingers on the front and 200μm large Al fingers at the rear. Loic Tous et al. simulate this efficiency by using numerical modeling Quokka 2 and calculate efficiency 21.3% due to higher J_{sc}= 40.2mA/cm^2 being simulated. They discovered that increase in efficiency from 21.3% to 21.5% through optimizing the pitch on rear side to 1mm when reducing both the Rs of Al fingers and developed resistance in 2Ωcm wafer. As the result, the simulated FF improves to 81.2%, indicating that losses of recombination in the emitter are limiting the cell [26].

Loic Tous *et al.*[27]designed features of modeled PERC+ cell for efficiency improvement through simulation method. Firstly improves the emitter because the emitter losses influence the total recombination losses. The metal fingers are reduced than reduces SRH recombination on the surface, and the V_{oc} increase by up to 16mV. In simulation method, a dash BSF pattern implanted to reduce losses instead of line BSF pattern. So width of laser contact opening reduced from 100 to $40\mu m$, dashes are 200μm large with 400μm pitch and screen-printed Al finger width is decreased from 200μm to 100μm implementing a reduction of contact pitch without negatively affecting bifaciality in the rear side. Absolutely, this leads to 23.9% efficiency. Finally, the efficiency may be increased to 24% by applying front double anti-reflecting coating (DARC).

T. Dullweber designed a solar cell with 70μm large poly-Si fingers under the Ag metal contacts, which could minimize the recombination of charge carrier significantly. PERC+ POLO is the name of this solar cell. The Numerical solution demonstrate that PERC+ POLO cells have a 24.1% efficiency potential, which is higher than PERC+ solar cell. The V_{oc} enhance with Ag front grid shadowing reduce and improve rear optics [28].

C. Zhanget al. investigated the p-type bifacial silicon solar cells fabrication. They used proper technical path to fabricate the cells. On both sides of solar cells, anti-reflecting coating and a finger contact were produced. For high rear efficiency, fingers on rear side with different height and width ratios, different rear SiN_x thickness. PERC+ with front and back efficiency above 22% and 15%, sequentially, were successfully generated in production line of a solar cell. Higher square resistance and lower square resistance can be combined by selective emitter on distinct regions to provide reduced recombination of charge carrier on higher square resistance regions and lower contact resistance at lower square resistance regions to achieve greater efficiency. More fingers were used in cell front side than in standard cells to absorb more photon-generated carriers and achieve high conversion efficiency. Selective Emitter (SE) PERC solar cell had a 0.35% efficiency improvement over conventional PERC cell, due to greater I_{sc} and V_{oc} values. The short circuit current value increase from 9.93A to 10.03A with 0.1 gain and the V_{oc} was increase from 0.657 to 0.673V. Alternatively, the SiN_X layer is too narrow, the Al paste it locally fire by the SiN_X layer than generating additional parasitic Al connection and increasing the recombination of contact, so influence cell efficiency. 95nm-thickness SiN_X was perfect for achieving the grater bifaciality factor (69.11%) and side efficiency 22.27% ($V_{oc} = 0.676V I_{sc} = 9.96A$ $FF = 80.13\%$), and the highest rear side efficiency 15.9% (V_{oc}=0.663V I_{sc}=6.98A FF=80.13%), which was comparable to that of a standard PERC cell[29].

T. Sugiura et al. studied numerical simulation based PERC+ structure with P and N-type Cz-Si parameters such as resistivity of bulk material, SRV of rear side passivation and pitch distance of rear contacts. This type of bulk doping can have a high effect on the overall performance of cell [30]. The bifacial structure limits the back contact area, resulting in increased back contact resistances and a decrease in fill factor (FF) performance. Because rear pitch distance (W_{rear})is related to the back-side shadowing, I_{sc} is the most significant constituent for the bifacial rear condition. So the rear side shading area reduces with the larger W_{rear}in the point-contact technique, and bifaciality factor rises. Improve the p-type bulk by greater SRV. On the other hand the bifacial condition needed a small area of rear contacts. For good rear side performance to require a larger pitch distance and rear illumination. [31].

G. Raina*et al.* investigate bifacial PERC cell under standard testing condition (STC) for different albedos. Calculate the performance metrics and properties of bifacial cell achieved SunSolve simulation. The albedo increases from 0 to 1 in fixed interval of 0.25 for purposes of this simulation. The impact of albedo on the bifacial solar cell is investigated. Measured the I-V characteristics of c-Si PERC+ solar cell underneath different albedo conditions. The results reveal that compared to monofacial solar cell, biPERC solar cell produces more power and I_{sc}. The parasitic absorption was also evaluated in the simulation and the results show that the absence of rear coating reduces parasitic absorptions, resulting in higher absorption of bulk and external quantum efficiency [32].

In a mass production line, laser-doped selective emitter has higher diffusion sheet resistance combine with several laser ablation designs on rear side and investigate the effects on electrical performance and passivation layer. Changing the nitrogen flow was used to adjust the diffusion sheet resistance. Improve the spectral response of short wavelength and passivation on rear side by reduced laser contact openings and high emitter sheet resistance and indicating real potential energy for highest efficiency and applications of bifaciality factor after further optimization. PERC solar cell passivation is heavily influenced through rear side ablation region. If laser ablation is smaller, damage passivation layer, as a result minority carrier lifetime and V_{oc} were high.

Table 1: Published Efficiencies of PERC+ solar cell

YEAR	ORGANIZATION	EFFICIENCY
2015	ISFH	20.8%/16.5% [9]
2015	Trina solar	20.3%/ [11]
2016	Big Sun energy Technology	20.7%/13.9% [12]
2017	ISFH	21.6%/17.3%
2018	IOSE	21.9% [20]
2019	ISFH(PERC+POLO)	24.1% [28]
2020	COMST	22%/15% [29]

Minority carrier lifetime reduced after laser ablation with straight lines. When compare straight lines with base line samples, the PERC+ efficiency with dash ablation increased by 0.29%. In mass production line a P-type PERC cell have front side efficiency improved 22.34% to 22.52% and bifaciality factor 76.8% to 78%. An Excellent mass production efficiency of 23.34% was recently achieved after using a multi-passivation structure and significant optimization, demonstrating for low- cost power generation [33].

2.3 Future outlook:

The global market share of bifacial cells is expected to increase from below 10% at the end of 2018 to more than 50% by the end of 2026. The influence of albedo or PERC+ cell structure must be studied in future research [32]. It is important to note that the PERC busbar number in mass production is still 5. The industrial cell can be raised to 22.4 to 22.9% by using 9 or 11 busbars. Future research is needed to develop high-quality p-type c-Si wafers that can withstand high temperature without reducing bulk lifetime, thus making P-PERT bifacial cells more cost-effective in real world application. Develop Al pastes with great fine line printing capabilities and bifaciality to increase rear side efficiency in future. Because PERC+ cells benefit from the continual technological innovation of monofacial PERC cells, further efficiency gain is expected in rear future [34]. To increase the contact resistance of phosphorous emitters that have been slightly doped. Increase the efficiency of biPERC solar cell to discover alternate materials for the surface passivation layer (other than SiN_x) and Al_2O_3) and increase bifaciality (the ratio of rear to front efficiency) while preserving front side efficiency.

Passivating contact to reduce carrier recombination is a common feature with total efficiency stronger than 24.5% in silicon solar cell [35,36]. Although, parasitic absorption of light is challenge which results decreased current especially when passivating contacts are used on the front side. Ideal electrical and optical properties achieved with Selective passivation contacts or metal oxides materials. [37]. According to modeling and comparisons with GaAs, as greater amount of minority charge carriers reaches the rear contacts, and electron reflectors can improve efficiency 28%. [38]. For requiring back surface passivation techniques, the rear surface recombination velocity is currently around 105-106cm /sec^{-1} [37].

For bifacial PERC solar cells, the main research activities are focused on removing Ag front contact with Cu plated contact. Since the silver supply is a significant cost for the cell. Cu-plated contacts can reduce high cost of silver, high temperature firing of Al/Ag paste and high recombination velocity which reduce efficiency with thickness of wafer.

Finger width reduction is one approach for enhancing efficiency and reducing cost, but only if it is realized without considerably increasing finger resistance. Furthermore, contact with shallow emitter is required. Using a selective emitter structure, preferably without increasing processing costs is one method to achieve these goals. We estimate that, bifacial modules will have a market share of more than 30%, with real bifacial modules accounting for more than 50% of all bifacial cells in 2029 [39].

If onewant to use inductively coupled plasma shadow mask deposition fingers on PERC+ POLO solar cells in future. Future research is needed on the mechanical stability during mask deposition, wafer handling and camera based arrangement of screen-printed Ag fingers to poly Si fingers on both sides. In general, a-Si finger shadow mask deposition is relevant for any solar cell design that uses poly-Si fingers on the front or back side. In coming years, we predict to improved laser contact opening (LCO) configuration and area of Al contact fraction to nearly 1% affecting the particular current density, J_o.

III. CONCLUSION:

The concept of PERC+ has been quickly approved by various solar cell manufacturer throughout the world in 2015 after first publication by ISHF and SolarWorld. In PERC+ cells, the open circuit voltage and short circuit current can increase when recombination of surface on rear side is decreased by introducing the passivation layer between silicon substrate and electrodes. Efficiency of p-type PERC+ has achieved 22.3-22.5%, with continuously optimization in industrialization technology, e.g., optimization in doped emitter, laser doped selective emitter, front surface antireflection and passivation, reduce losses in shading and contact electrodes. Despite the fact that many research institutes are focusing on the n-type bifacial PERC because there is no induced degradation of light compared to p-type. But the generation of emitter and BSF for n-type is more difficult and complicated than for p-type, and because the cost is higher due to use of silver paste on both sides. P-type bifacial solar cell has advantages and the best chance of becoming one of the main structures in future.

Furthermore, Al fingers changes the alloying characteristic during furnace firing in Al-BSF as a result open circuit voltage is higher in PERC+ Cells than PERC cells. Different challenges of industrial PERC+ solar cells are high specific resistivity of Al fingers, Al paste at rear, high specific alignment between laser contact opening and Al screen printing. Different challenges are resolved through advance modules designs, such as 5 busbars or smart wires, enhance fine lines capabilities of Al pastes, and an alignment of camera based method among laser and printing techniques.

Bifacial PERC+ modules of smart wires technology (SWCT) is an attractive possibility. The thickness of SiN_X on the bifacial solar cell's rear surface affects the cell's performance only on the rear side. As a result, by improving the rear SiN_X layer, the rear efficiency might be enhanced. Alternative, in the rear $SiNx:H/Al_2O_3$ stack film provides an excellent rear surface passivation. Double layer anti-reflecting coating (DARC) film consist as anti-reflecting layer of rear side to attain a highest optical generated current density. So double-printed PERC+ (SE) has achieve good efficiency. When increased the finger width and decreased rear film thickness, the electrical performances and external quantum efficiency has changed. For contact formation, the recombination and shading losses due to screen-printing metallization at front contact get reduced using Cu/Ag plated narrow fingers. Optimizing the laser contact opening pattern such as line or dash, the rear electrode area can be reduced which results in minimizing recombination.

The electrical resistance associated with contacts and fingers must be decreased to optimize metallization for metal contact formation and finger coverage should be kept low to reduce optical losses. Double printing can be utilized to improve the aspect ratio without increasing the contact area. Smaller contact area and reduce shading increases the V_{oc} and I_{sc} with a higher absolute efficiency and less Ag paste utilization.

When high surface recombination occurs caused by laser damage surface hence both V_{oc} and I_{sc} gets affected. So laser ablation technique is used at rear side passivation layer to decrease the minority carrier lifetime. Which means that higher potential to improve the V_{oc} and reduce damages. The solar cell temperature has a high impact on the photovoltaics efficiency. When increase surface temperature of solar cell than efficiency decreases because open-circuit voltage decreases. Simulation and modeling of N-type PERC+ exhibit higher efficiency higher efficiency compared to P-type PERC+. Further research has been focused on the efficiency improvement of PERC+.

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