White Paper

PERC Solar Modules: Risks and Mitigation Strategies

By Dan Chawla and Todd Tolliver, ICF

Shareables

- PERC technology enables module powers as high as 365 W today with the potential to be as high as 420 W in the future.
- Solar modules incorporating PERC cells are expected to increase in market share from 14% in 2016 to more than 40% in 2021.
- There is a new power degradation mechanism associated with PERC modules. Detailed manufacturer due diligence is required to understand if this risk has been mitigated.

Executive Summary

The photovoltaic industry has been dominated by one primary solar cell and module technology for more than ten years – Aluminum Back Surface Field ("Al-BSF"). However, Al-BSF technology is near its practical limit and further gains in efficiency are unlikely. The search for continued efficiency improvements has led the industry to adopt Passivated Emitter and Rear Contact ("PERC") solar cells. PERC cells have unlocked access to higher module powers – up to 365 W for a 72-cell module (compared to 335 W for Al-BSF technologies) and have a pathway to powers as high as 420 W.[1]

[1] B. Min, "Incremental Efficiency Improvements of Mass Produced PERC Cells Up to 24%, Predicted Solely with continuous development and existing technologies and wafer materials," in 31st European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, 2015.

As of 2016, PERC cells had captured 14% of the total global market share and there were 23 manufacturers with PERC modules in production. This share is expected to grow to more than 40% by 2021 and could replace almost all Al-BSF production by 2027.[2] PERC cells are a natural progression of the Al-BSF architecture and utilize similar materials and manufacturing processes, but there is potential for new degradation mechanisms that may impact the ability of photovoltaic projects to generate energy. Managing the risk of these degradation mechanisms requires an understanding of the similarities and differences between PERC and Al-BSF modules, the changes made to manufacturing processes to produce PERC cells, and the impact of these on long term performance of modules.

What is PERC?

Losses that limit the efficiency of a silicon solar cell can be separated into three broad categories – the bulk silicon, the front surface, and the rear surface. Bulk silicon losses are controlled by the quality of the silicon material used, while front and rear surface losses are controlled by a passivation treatment applied to the silicon surface. Passivation removes defects in the atomic structure at the silicon surface allowing more efficient extraction of energy from the solar cell. Exhibit 1 shows the design of a PERC and an Al-BSF cell. Note that the cell designs are very similar except for the rear surface. In an Al-BSF cell, only the front surface is passivated using a thin layer of silicon nitride ("SiN") which serves as both a passivation layer as well as the cell's anti-reflective coating. Rear surface losses are dominant and drive the efficiency of the cell. In a PERC cell, both the front and the rear of the cell are passivated leading to an improvement in how efficiently the cell is able to convert light to electricity.

Additional Manufacturing Steps

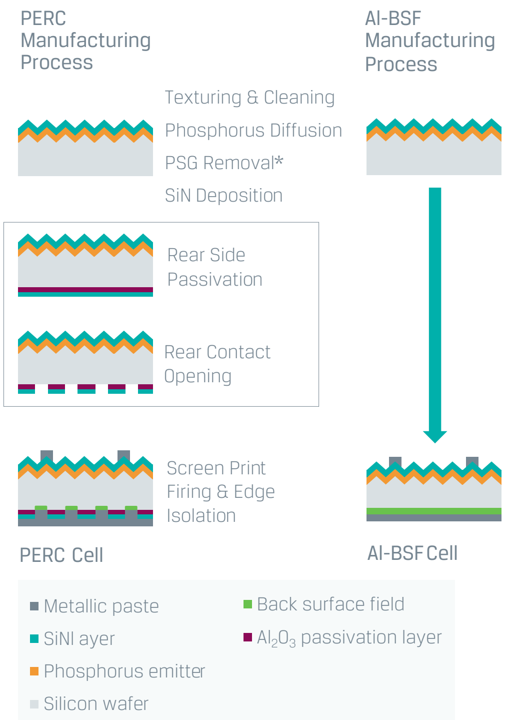
The rear surface of a PERC cell is improved by the addition of two steps in the cell manufacturing process – rear side passivation and rear contact opening. Plasma Enhanced Chemical Vapor Deposition ("PECVD") combined with Aluminum Oxide ("Al_2O_3") and SiN has emerged as the process of choice for rear side passivation with 90% of the industry adopting this method. This is primarily due to the fact that PECVD is a mature production technology and has been used to deposit the front surface SiN layer of Al-BSF cells for almost a decade by the majority of manufacturers. There are a number of established equipment companies that have developed solutions to address the PERC rear side passivation market – Centrotherm, Meyer Burger, Manz, Schmid, Singulus and others. Meyer Burger has emerged as a major player, shipping 12GW of PERC tools in 2016 and securing more than 7GW of PERC tool orders in the first half of 2017.[3] [4]

[2] ITRPV, "International Technology Roadmap for Photovoltaics Eight Edition," 2017.

[3] M. Osborne, "Meyer Burger secures follow-on PERC upgrade orders worth US$82.4 million," PVTech, 31 05 2017. https://www.pv-tech.org/news/meyer-burger-secures-follow-on-perc-upgrade-orders-worth-us82.4-million

[4] S. K. Chunduri and M. Schmela, "PERC Solar Cell Technology 2017 Edition," Taiyang News, 2017

EXHIBIT 1: PERC CELL DESIGN PROCESS



(Left) The PERC Cell design and manufacturing process. (Right) The Al-BSF cell design and manufacturing process. (box) Extra process steps associated with the PERC cell. *The phosphosilicate glass ("PSG") removal step needs to be optimized specifically for PERC to planarize the rear of the cell.

One of the steps after rear side passivation in the cell manufacturing process involves adding metallic contacts to the cell that will allow multiple cells to be connected together in the module. This is accomplished by screen printing a grid of metallic paste onto the front and rear surfaces of the cell (see Exhibit 1). However, after the rear side passivation step is completed, the rear surface of the PERC cell is electrically insulating. Screen printing over this surface would not allow an electrical contact to be established. The metallic contact needs to be able to reach the silicon under the passivating layers (Al_2O_3, SiN) in order for current to flow through the cell. An additional manufacturing step called rear contact opening is required to accomplish this. Holes are created in the passivating layers that will allow the metal to contact through to the silicon. The most common method used for this is laser ablation, a process that removes material from a solid surface by irradiating it with a laser beam. The equipment manufacturer market for laser ablation is very crowded with no specific company in a dominant position. Most of the established players are having to compete directly with newer low cost suppliers from Asia.

New Materials

Addition of new materials to any solar component can lead to higher level of risk for a project. New materials can respond to environmental factors in unforeseen ways leading to new failure mechanisms. Two materials that are added to the PERC cell and are not in the standard Al-BSF cell are the passivation layer, added during rear side passivation, and a metallic paste with a different composition, added during screen printing. An ideal passivation layer needs to be able to chemically passivate the rear surface of the cell, survive the subsequent manufacturing steps (screen print, firing), be cost effective, and have minimal impact on the reliability of the module. Al_2O_3 has been shown to be excellent at passivating the surface of silicon.[5,6] Unfortunately, it is not cost effective when produced to survive subsequent manufacturing steps and its reliability over the 25 year module lifetime is unproven. A robust solution to these problems involves covering the Al_2O_3 layer with a thicker SiN layer. SiN has been used as a passivating layer for the front surface of Al-BSF cells for more than a decade. It is stable during the screen print and firing steps and cost effective for industrial applications. It has also been shown to be able survive the rigors of module reliability testing and field installation. Addition of the SiN protects the Al_2O_3, significantly reducing the risk of any unforeseen degradation that could occur over the lifetime of the module.

The front and rear electrical contacts of Al-BSF and PERC cells are relatively similar. This has allowed cell manufacturers to continue using the conventional screen printing and firing processes for these contacts. However, the unique characteristics of a PERC cell require a metallic paste with a different composition to be used during the screen printing process. As of early 2017, a number of reputable paste manufacturers were offering PERC specific products.[7]

[5] J. Schmidt, "Progress in the Surface Passivation of Silicon Solar Cells," in European Photovoltaic Solar Energy Conference, Valencia, 2008

[6] B. Hoex, "Ultralow surface recombination of c-Si substrates passivated by plasma assisted atomic layer deposited Al2O3," Applied Physics Letters, vol. 89, no. 4, 2006

[7] S. K. Chunduri and M. Schmela, "Market Survey: Metallization Pastes 2017," Taiyang News, 2017

The metallic paste is the point of contact between the cell and the rest of the module. As much as 40% of all module failures that occur during the International Electrotechnical Commission ("IEC") 61215 standard battery of module tests occur at these connections during the temperature cycling step.[8] Any change to the paste means that the long- and short-term behavior of the module could be affected. This risk can be mitigated by repeating the IEC tests for modules that are upgraded with PERC cells and temperature cycling the modules beyond the 200 cycles required by the standard test.

Degradation Mechanisms

Solar modules have traditionally suffered from three primary degradation modes: Potential Induced Degradation ("PID"), Light Induced Degradation ("LID") and Yearly Degradation. PID is caused by the voltage difference that occurs between solar cells and the grounded module frame. The primary mechanism for PID in conventional Al-BSF modules is migration of ions from the front glass into the front junction of the solar cell that leads to shunting and power loss.[9] There is no evidence in the literature that PERC cells are any more susceptible to PID than Al-BSF cells. Any PID test developed for a conventional Al-BSF module can be applied to a PERC module with similar results. The current standard within the industry is IEC 62804.

Yearly, or long-term, degradation is the annual power loss experienced by a field deployed solar panel. This is a generic term used for a number of failure mechanisms related to environmental factors such as water ingress, temperature stresses, mechanical stresses and UV light. Some examples include corrosion of contacts, deterioration of the anti-reflective coating, cell cracking and delamination of the encapsulation. Module warranties and estimates for modeling of solar power projects in the United States generally assume a linear loss of 0.5%-0.8% per year for the majority of conventional Al-BSF modules. This is based on an extensive study conducted by the National Renewable Energy Laboratory ("NREL") of degradation rates of modules in solar projects. In general, these mechanisms are not related specifically to cell technology. Furthermore, PERC and Al-BSF cells are similar enough that the same module materials and manufacturing are used for both. It is reasonable to expect that PERC modules would display a yearly degradation comparable to Al-BSF modules.

Light Induced Degradation

LID occurs when solar cells and modules are exposed to light. In Al-BSF modules, LID results in a power loss of 1-3% depending on the type of technology utilized – multi-crystalline or mono-crystalline. LID was first reported in the 1970s and there is consensus within the industry on its causes and on ways to suppress it.

[8] R. Arndt and I. R. Puto, "Basic Understanding of IEC Standard Testing For Photovoltaic Panels," Compliance Magazine, 2010

[9] P. Hacke, "Test-to-Failure of crystalline silicon modules," in 35th IEEE Photovoltaic Specialists Conference (PVSC) , Honolulu, 2010

The primary cause is an interaction of boron and oxygen atoms present in the silicon resulting in a reduction in the performance of the material.[10] [11] This mechanism is less apparent for multi-crystalline cells because they have a low concentration of oxygen. For mono-crystalline cells, the process used to produce the silicon material results in a higher oxygen concentration and the LID impact is more pronounced. The level of LID is also dependent on the quality of silicon material used and can vary between manufacturers. Testing with silicon material that is free of boron or oxygen, like n-type silicon, has been shown to almost eliminate LID. It can also be suppressed with optimizations of the cell manufacturing process and post manufacture annealing.

PERC cells manufactured using mono-crystalline technology are particularly sensitive to LID as compared with Al-BSF cells. The material quality of the silicon has a greater impact on the efficiency of a PERC cell because the front and rear surfaces are passivated. As PERC cells have emerged as the next step in cell technology and become more common, LID has become a limiting factor. A number of reputable equipment manufacturers have taken the additional step of offering LID suppression tools for PERC cells with some even willing to guarantee the level of LID reduction.[12] These suppression tools can reduce the LID observed in PERC cells from 3-5% to 1-3%, such that it is comparable to Al-BSF cells. However, the risk associated with LID in PERC modules is still higher than with standard Al-BSF modules. While a number of third-party labs offer LID testing and certification, there is no IEC or Underwriters Laboratories ("UL") standard specifically for LID. Field data and long term LID testing (6-12 months) are the only ways to completely understand the magnitude of this risk, and whether LID has been suppressed for a given module.

Light and Elevated Temperature Induced Degradation

Recently, multiple research groups have shown that both multi-crystalline and mono-crystalline PERC modules can degrade severely (up to 15%) when exposed to both light and temperatures above 50˚C.[13]w [14] The consensus within the industry is that this degradation is not caused by the traditional boron-oxygen mechanism associated with LID and a new term has been proposed – Light and Elevated Temperature Induced Degradation ("LeTID"). The impact of LeTID on a module in the field can be both significant and unpredictable.

[10] B. Sopori, "Understanding light-induced degradation of c-Si solar cells," in 38th IEEE Photovoltaic Specialists Conference (PVSC), Austin, 2012

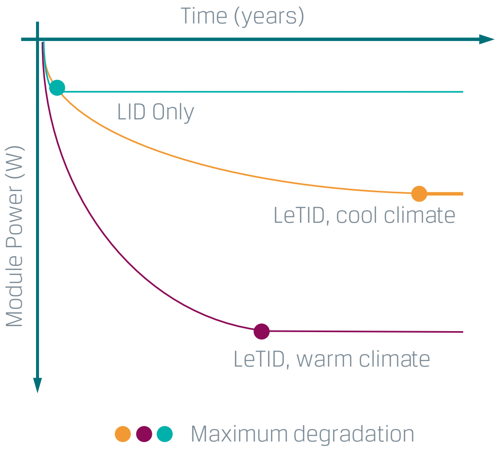
[11] J. Schmidt, "Structure and transformation of the metastable boron- and oxygen-related defect center in crystalline silicon," Physical Review B, vol. 69, no. 2, 2004

[12] G. Fischbeck, "Keep a LID on it," PV Magazine, 2010

[13] K. Ramspeck, "Light Induced Degradation of Rear Passivated mc-Si Solar Cells," in 27th European Photovoltaic Solar Energy Conference and Exhibition, Frankfurt, 2012

[14] D. Chen, "Evidence of an identical firing-activated carrier-induced defect in monocrystalline and multicrystalline silicon," Solar Energy Maerials and Solar Cells, vol. 172, pp. 293-300, 2017

EXHIBIT 2: DEGRADATION IMPACTS



Estimated Impact of LID and LeTID on module power. Note that the maximum degradation level and the point in time when it occurs is dependent on the type of degradation mechanism (LID or LeTID) and the temperatures a module is exposed to in the field. (Plot is not to scale)

As of summer 2017, there is no consensus about the exact mechanism associated with LeTID. It has been shown that LeTID can vary based on the material properties of the silicon utilized, as well as the cell manufacturing process.[15 16] Since the effect occurs only at elevated temperatures, it will not manifest completely in the early stages of module deployment and can be difficult to observe in the field.

Exhibit 2 shows the estimated impact of LID and LeTID on module power. Note that the maximum degradation level and the point in time when it occurs is dependent on the type of degradation mechanism (LID or LeTID) and the temperatures experienced by the module in the field. Measurements of field deployed modules have shown that in Germany, where average temperatures are low, a multi-crystalline PERC module degraded by 2.5% over three years, while a similar module degraded by 8% in the warmer climate of Cyprus, during the same period of time. Researchers estimate that LeTID could take as long as 10 years to reach its maximum impact in a low temperature country like Germany. The impact of this level of degradation on the Levelized Cost of Energy ("LCOE") and the Return on Investment ("ROI") of a project would be significant. Large scale deployment of PERC modules requires that reliable suppression strategies be developed for LeTID.

Industrial LID suppression techniques and tools cannot be applied directly to LeTID as the mechanism associated with each is different. However, some convincing suppression strategies have been presented in the literature for LeTID – (a) regeneration using illumination and high temperatures, (b) careful wafer material selection, and (c) reduced peak temperatures during the firing process.[17 18]

Companies that have been working with PERC cells for an extended time, like Hanwha Q-cells and REC, claim to have found solutions to LeTID.[19] Researchers from Hanwha Q-cells have shown convincing field results of their suppression strategy in the literature but have been unwilling to reveal details about their proprietary technology.[20] Equipment manufacturers are working diligently to develop commercial tools for LeTID suppression based on the approaches in the literature. However, these tools are not yet available and the knowledge base associated with LeTID suppression is limited.

[15] D. Bredemeier, "Measures for Eliminating Light-Induced Lifetime Degradation in Multicrystalline Silicon," in 32nd European Photovoltaic Solar Energy Conference and Exhibition, Munich, 2016

[16] K. Nakayashiki, "Engineering Solutions and Root-Cause Analysis for Light-Induced Degradation in p-Type Multicrystalline Silicon PERC Modules," IEEE Journal of Photovoltaics, vol. 6, no. 4, pp. 860-868, 2016

[17] D. Payne, "Acceleration and mitigation of carrier-induced degradation in p-type multi-crystalline silicon," Phys. Status Solidi RRL, vol. 1, no. 5, 2016

[18] C. E. Chan, "Rapid Stabilization of High-Performance Multicrystalline P-type Silicon PERC Cells," IEEE Journal of Photovoltaics, vol. 6, no. 6, pp. 1473 - 1479, 2016

[19] REC-Solar, "The REC TwinPeak Series: How improvements in production lead to better degradation resistance," 2015. http://www.recgroup.com/sites/default/files/documents/whitepaper_twinpeak_lid_resistance.pdf

[20] F. Kersten, "System performance loss due to LeTID," in 7th International Conference on Silicon Photovoltaics, Freiburg, Germany, 2017

What Diligence is Required for PERC Modules?

There are risks associated with any new technology entering the market. In the case of PERC cells, the changes to the cell design and the materials added to the cell do not have a significant risk associated with them. In the case of PERC modules, PID and Yearly Degradation are unlikely to be changed because PERC cells utilize the same module materials and manufacturing as Al-BSF cells. The primary risks are a higher susceptibility to LID and the newly discovered LeTID mechanism. The mechanism behind LID in PERC modules is well understood and has a long research history associated with it. LID suppression tools designed for PERC cells are available on the market from several reputable equipment manufacturers. The standard LID test developed for Al-BSF modules can be applied to PERC modules to test the effectiveness of LID suppression treatments. It is reasonable to make LID assumptions comparable to conventional Al-BSF modules for a PERC module if: a) the module is from a manufacturer that is applying a LID suppression treatment, b) LID test data has been used to confirm the effectiveness of this treatment and c) some long term field data (6-12 months) is available for review.

In the case of LeTID, the research base is relatively small and the mechanism behind it is not well understood. LeTID suppression techniques are still in the development phase and no off-the-shelf solution is available. The consensus within the industry is that a test for LeTID must involve exposure to light and temperatures above 50˚C but there is no standard test available. Furthermore, there is no standard way to model LeTID since the degradation in the field is weather dependent. The potential 15% power loss associated with LeTID would have a significant impact on the LCOE and ROI of a solar project. When considering a PERC module for deployment, focus should be applied to understanding the effectiveness of the manufacturer's LeTID suppression strategy. Results of laboratory tests involving elevated temperatures and light exposure, as well as long term field data, should be reviewed to ensure LeTID is being suppressed. Until consensus is built within the industry on LeTID suppression methods and more field data for PERC modules becomes available, significant due diligence must be conducted to mitigate the risk associated with these modules.

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About the Authors

Dan Chawla specializes in solar photovoltaic technology with almost a decade of experience in R&D, manufacturing and product management. He has served as an independent engineering representative for multiple solar energy projects and as the technical expert for due diligence associated with large investments in solar manufacturing ($3-5B) and solar company acquisitions ($400-$500M). He has extensive experience working with solar manufacturers in the US, China, Korea, Malaysia and India. Dr. Chawla developed his expertise in technology by working in early stage R&D, with manufacturing sites in multiple countries, conducting due diligence on investments, and supporting independent engineering reviews of solar projects.

Todd Tolliver has over thirteen years of experience in the field of photovoltaics working in the research of and manufacture of photovoltaic materials, solar cells, and modules. He supports clients through technical due diligence and owner's advisory services and has leveraged his knowledge of solar materials, technology, and manufacturing to support 500 megawatts of solar photovoltaic projects. Mr. Tolliver specializes in component technology reviews, system performance modeling, and project management for photovoltaic and energy storage systems in support of project finance and other asset transactions.

For more information, contact:

Dan Chawla
dan.chawla@icf.com +1.970.372.3941

Todd Tolliver
todd.tolliver@icf.com +1.970.372.3931

twitter.com/icfi
linkedin.com/company/icf-international
facebook.com/ICFInternational/