Scientific Achievement Highlights, 2016

Research Achievements

- Record cell efficiency of 23.5% for 156*156mm² IBC Si solar cell
- Record cell efficiency of 19.86% for P-type Honey Plus polycrystalline Si solar cell
- Record cell efficiency of 22.61% for P-type monocrystalline Si PERC solar cell
- Cell efficiency of 22.40% (tested in laboratory) for 6-inch bifacial N-type PERC cell
- Cell efficiency of 21.4% for 6-inch bifacial N-type PERT cell in pilot production

Awards

- Dr. Pierre Verlinden was honored with 2016 William R. Cherry Award in 43rd IEEE PVSC
- DUOMAX dual glass solar module was the first to pass the latest accreditation criteria of ‘Top Runner’ Dual Glass Solar Module Technical Specifications
- Osaka Sangyo University’s solar cell, equipped with Trina Solar’s IBC solar modules, won the championship of ‘Dream Group’ in the 2016 FIA Solar Car Race
- Trina Solar was among the first batch in China to pass NIM (National Institute of Metrology) module power measuring uncertainty assessment certification
- Invention patent (No. of ZL201210141633.5) - 13th Patent Golden Award of Changzhou and 18th China Patent Excellence Award for interdigitated back contact solar cell fabrication method
- Trina Solar received the Second Prize of 2016 National Federation of Industry and Commerce Sci-Tech Advance Award

Scientific Papers & Patents & Standards

- Scientific papers: 36 papers published in scientific journals and key international PV conferences
- Patents: 97 patents approved including 38 invention patents
- Published Standards: industrial standards of specification for ultra-thin glasses used for photovoltaic modules (SJ/T 11571-2016), graphical symbols for solar photovoltaic energy systems (SJ/T 10460-2016)

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VISION

◆ Reduce cost by efficiency improvement; Attain development through technical innovation.
◆ Bring solar energy to every household.

MISSION

◆ Benefit mankind with solar energy!
Driven by a strong business case and falling costs, photovoltaic energy has progressed remarkably over the past decade, and has become the preferred power source for many countries, paving the way for a revolution in the electrical system in countries around the world. On a global level, the weighted average levelized cost of electricity (LCOE) for utility-scale solar PV has reached USD 0.13/kWh in 2015 and is forecasted to fall by 59% by 2025 with the right policies. The upfront cost of building a solar PV plant is now close to or even lower than that of a conventional power generation plant. While the solar PV offers enormous opportunities, it currently provides less than 2% of global electricity today and a higher level of penetration, especially beyond 20% grid integration, will only come about with a host of new activities such as demand-side management, electrification of the transport and integration with buildings etc. In order for these new activities to foster, efforts to increase PV efficiencies and lower costs should be encouraged and pursued – PV efficiencies over 40% will allow for radically different uses such as integration into electric vehicles, and combined with lower costs, will open up incredible new opportunities for solar PV deployment in urban environments. Supported by our core mission - i.e. to develop a cheaper photovoltaic solar energy to benefit mankind by developing leading PV techniques and products that improve the efficiency and reduce the system cost – our researchers and scientists are working towards such future.

2016 has been a rewarding year for the State Key Laboratory of Photovoltaic Science and Technology (SKL of PVST) - numerous world records have been achieved; new mobile PV team has been established in response to the special and new market demand; and academic collaborations and exchanges with PV experts around the world have continued to flourish.

This year, we are very honoured to welcome Professor Martin Green as our academic committee member. Professor Martin Green, often known as the “Father of Photovoltaics”, has over 40 years of PV research career and made distinctions to both commercial and academic fields of photovoltaics. He has set numerous world records for silicon based solar cells and pioneered the field of “third generation” photovoltaics which investigates advanced, for silicon based solar cells and pioneered the field of “third generation” photovoltaics which investigates advanced, high-efficiency photovoltaic device concepts in order to re- design the fundamental limits of solar cell efficiency. We look forward to collaborating on the high-efficiency PV device programmes at SKL of PVST.

We would like to congratulate Dr Pierre Verlinden, the Chief Scientist and Vice-President of Trina Solar and the Vice-Chair of the State Key Laboratory, who has been selected, in June, as the 2016 William R. Cherry award recipient for his dedication over the past three decades at the past three decades at the forefront of PV technology research and commercialization, and his overall leadership at key R&D organisations.

As leaders of the SKL of PVST, Dr Pierre Verlinden and I feel very honoured and thank all the teams of PV researchers and scientists who have enhanced Trina Solar’s key PV technologies through innovation that have resulted in several world record cell and module efficiencies in recent years. We will also like to take this opportunity to congratulate two of our great PV researchers, Dr Qiangzhong Zhu and Dr Weiyuan Duan, who have received Excellent Scientific Paper Award at the 16th China Photovoltaic Technical Conference in October.

The SKL of PVST was invited to produce high-efficiency IBC solar cells again for the Osaka Sangyo University (OSU) Solar Car, following the successful collaboration last year. With improved process optimisation, the average efficiency of the cells provided this year was 23.5%, 0.5% higher than that of last years. The OSU Solar Car won the “Dream Class” category this year where the racing car was required to largely depend on the power generation capacity of the solar cells rather than the battery’s, and required the team to carefully manage the energy consumption during the 5-hour race.

Our successful collaboration with solar racing cars instilled in us a vision of incorporating high-efficiency PV products into commercial cars and this year we set up a mobile PV team to foster technology collaboration with the automobile industry. Our mobile PV team is working with premium automobile companies in Japan and Europe whereby Trina Solar provides solar cells for car roofs of their electrical vehicles to power the internal temperature regulation management system. Similar contracts have also been successfully negotiated for the public transport in India.

Within the four walls of our Laboratory, a great progress in ingot and wafer research has been achieved. 1) High quality multicrystalline wafer labelled as T1 (Trina 14) reached the state-of-the-art wafer level in the market and was employed in the high-efficiency cell production line; 2) Diamond wire slicing technique for the multicrystalline ingot was explored successfully. The total yield was up 90% with remarkable cost reduction; 3) The multicrystalline ingot research has also been rewarding - the pulling speed reached up to 1.25 mm/min at 53 kW power. We believe that the high quality wafer is not only beneficial to the cell efficiency and module power output, but also to the module reliability.

In April this year, our high-efficiency solar cell team set a new world record of 23.5% with an IBC structure on a large-area (156x156mm²) n-type mono-crystalline silicon wafer. The solar cell was fabricated entirely with low-cost industrial screen-printed processes. This record not only broke the previous record of 22.94% for the same type of solar cell that was also set by the Laboratory in May, 2014, but follows the previous record of 24.4% small-area (2x2cm²) laboratory IBC solar cell developed just two years prior, in collaboration with the Australian National University (ANU). To the best of our knowledge, this was the first time that a mono-crystalline silicon IBC solar cell on a large-area (6-inch) wafer reached a total area efficiency of 23.5%. In July, the average output of a 60-cell p-type mono-crystalline module constructed with standard industrial production materials and processes reached 300W by assembling PERC cells with an average cell efficiency of 21.1%. The said 21.1% average efficiency was a major improvement breakthrough for the industrial mono-crystalline PERC cell and demonstrated the Laboratory’s technological strength in transferring laboratory technology to mass production. Shortly thereafter in the same month, the Laboratory further solidified the leading position in cutting-edge PV technology for the mass production of high-efficiency PV products by achieving an average efficiency of 20.16% for its p-type multi-crystalline PERC cells produced with industrial processes. The cell was built with advanced PERC technology and materials developed at the Laboratory including high-performance p-type Trina 1 wafers. In October, the Laboratory set another world record for a p-type multi-crystalline PERC module aperture efficiency. Consisting of 120 pieces of “half-cell” (156x78mm²), the module was independently developed with high-performance wafers and advanced in-house module technologies and its aperture efficiency reached 19.86%. The new record presents an increase of more than 0.7% <<sub>ap</sub> or approximately 3.8% higher than the previous aperture efficiency record of 19.14% announced a year and half earlier. We are very excited about this achievement as it demonstrates the huge potential for the future multi-crystalline p-type silicon research. In December, the self-developed P-type PERC solar cell has created another world record with the conversion efficiency reaching up to 22.61%, which is the highest efficiency achieved for the large-area industrialized P-type mono-crystalline PERC solar cells.

Our module team continued commendable work this year by transferring high-efficiency laboratory module technologies to the mass production. The first climate-specific advanced Duomax double glass module, Sahara, is now mass-production ready as well as the 120-half cell- p-type mono-crystalline module, Splitmax. Sahara, as the name suggests, has been developed for dry and sandy regions that experience cycles of extremely high and low temperatures. First in its series, the linear degradation of Sahara module’s maximum power output is 0.12% (annual) lower than that of the conventional double glass module. The continued improvement effort on the Duomax double glass was recognised in July when it became the first PV module to have obtained the accreditation as part of the Chinese government led ‘Top Runner’ programme. Meanwhile, we have successfully developed Splitmax module product, which is composed of 120 P-type mono-crystalline half cells.

In the area of patents, Trina Solar still holds the highest number of invention patents amongst the Chinese PV manufacturers this year. For the year 2016, 106 patents have been filed and 97 patents have been approved. Of the 106 patents, 51 patents are invention patents highlighting the Laboratory’s lead on innovation. Cumulatively, as of December 31, 2016, 1317 patents have been filed by Trina Solar and of those, 597 are invention patents. In the area of standards, the Laboratory has participated in 64 standards in total as of December 2016. 45 standards have been published including 10 guided standards. 14 standards under research include IEC standard, 4 SEMI standards, 5 national standards and 4 industry standards.

As we reflect on the many achievements in 2016, we would like to thank all the dedicated and hard-working teams and stakeholders. Thank you for your commitment to building a world where PV plays a vital role in benefiting mankind.

Dr. Zhiqiang Feng
Vice President of Changzhou Trina Solar Energy Co., Ltd
Director of the State Key Laboratory of Photovoltaic Science & Technology
December 31, 2016
Chapter 1 Organizational Structure

- 1.1 Senior Management
- 1.2 Academic Committee
- 1.3 Research and Development Groups
In January 2010, the plan to establish the State Key Laboratory for Photovoltaics Science and Technology (SKL PVST) establishment was approved by the Ministry of Science and Technology (MOST). In November 2013, SKL PVST was successfully accredited by MOST, becoming one of the only two State Key Laboratories set up within a PV company in China.

SKL PVST is responsible for establishing fundamental PV science and technology research platforms, attracting and cultivating PV talents, promoting industry collaborations and exchanges, and successful technology transfer to the mass production.

There are 163 researchers and scientists including 20 with PhD working in five key research centers, the golden line & pilot line, the testing center, and the office. The bulk of the research work is dedicated to the crystalline silicon solar cell. The golden line and the pilot line optimize laboratory technologies before transferring them to the mass production line.

State Key Laboratory for Photovoltaic Science and Technology

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Senior Management

SKL PVST, supported by Changzhou Trinasolar Energy Co. Ltd., is managed by an academic committee which provides guidance for current and future research directions. There are five research departments* that it supervises. It also oversees the pilot line, one testing laboratory which has been heavily invested over the years to ensure continuous product quality and reliability, and an administrative office which facilitates the smooth running of all departments.

*Five research departments are: 1) Crystalline Silicon Solar Cell Material Research Center, 2) Crystalline Silicon Solar Cell Research Center, 3) PV Module & New Product Research Center, 4) PV System Research Center, and 5) Equipment Research Center.
1.2 Academic Committee

Each year, the Academic Committee provides guidance for the upcoming R&D programs and sets targets for SKL PVST.

### Director of Academic Board

**Hui Shen**
- Professor of Physics and Engineering College of Sun Yat-Sen University
- Director of Solar Energy Institute of Sun Yat-Sen University
- Director of Key Laboratory of PV Technology in Guangdong Province

### Deputy Director of Academic Board

**Pierre Verlinden**
- Vice President & Chief Scientist at Trina Solar
- Distinguished specialist of first batch of National ‘The One Thousand Foreign Expert’
- Member of IEEE PVSC Committee

### Members of Academic Board

<table>
<thead>
<tr>
<th>Name</th>
<th>Position and Affiliation</th>
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<tbody>
<tr>
<td>Martin A. Green</td>
<td>Scientia Professor at UNSW, Director at Centre for Advanced Photovoltaics</td>
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<tr>
<td>Junhao Chu</td>
<td>Academician at CAS, Professor at Shanghai Institute of Technical Physics of CAS</td>
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<tr>
<td>Pietro Altermatt</td>
<td>Principle Scientist at Trina Solar</td>
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<td>Thomas Rheindl</td>
<td>Deputy CEO at Solar Energy Research Institute of Singapore</td>
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<td>Liangjun Ji</td>
<td>Researcher at UL in the USA, Assistant Secretary-General of IEC/TC82</td>
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<td>Deputy Director at Fraunhofer ISE</td>
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<td>Deren Yang</td>
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<td>Zhen Zhang</td>
<td>Professor at Hohai University, Group leader of PV modules &amp; system at Trina Solar</td>
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1.3 Research and Development Groups

Crystalline Silicon Solar Cell Research Center

The group’s main aim is to develop and promote high-efficiency crystalline silicon growth technologies suitable for mass production and was the first to introduce the Direct Wafers technology in China. The group is also responsible for the diamond wire cutting technology used for multicrystalline silicon wafers, the cleaning technology of recyclable silicon materials, and the recycling technology of abandoned solar modules.

Crystalline silicon solar cell research center is responsible for the research of crystalline silicon solar cell structures ready for commercialisation which involves theoretical simulation and characterization of high-efficiency solar cell structures. It is also responsible for the development of key solar cell processes such as light-trapping, multi-layer passivation and metallization, as well as the development of high-efficiency crystalline silicon solar cell structures.

The group also works closely with the manufacturing line to transfer the latest technical achievements to the mass production line. For example, the laboratory PERC research achievements were transferred to the manufacturing line in 2016, which is now producing a stable average cell efficiency of 21% and a stable solar module output power of 300Wp.

PV Module & New Product Research Center

PV module & new product research center focuses on developing and optimizing smart PV modules & systems, and PV system tests. In particular, the group focuses on developing differentiated PV module technologies and installation structures, optimizing PV module manufacturing processes as well as on an in-depth study on PV modules’ reliability and degradation mechanisms. In particular, the group’s latest achievement was the establishment of indoor module reliability tests that emulate the real-world cyclic climate conditions.

PV System Research Center

PV system research center focuses on developing and optimizing smart PV modules & systems, and PV system tests. In particular, the group focuses on developing differentiated PV system components that promote low LCOE. The group routinely maintains the PV system testing laboratory which assesses system components’ engineering and operation in both indoor and outdoor settings, and provides consultation to Trinasolar’s sales group on system design and component selection. The latest achievements include “internet-plus” applications, a 1500V PV station, smart PV system for households and participation in PV system standards.
Equipment Research Center

Equipment research center focuses on developing new laboratory equipment and procuring them locally, as well as promotion of R&D equipment for industrialisation. The group is also responsible for equipment management and routine maintenance of the golden line, the pilot line, the solar cell laboratory and the testing center, as well as equipment upgrades.

Golden Line & Pilot Line

The golden line and pilot line are responsible for successful technology transfer from laboratory to the mass production line. It ensures that the processing techniques of the latest technology are suitable for mass production, and that these techniques can produce a consistent and stable throughput. Since its inception in 2013, the conventional solar cell efficiency at Trina Solar went from 17.5% to 18.1%. An implementation of numerous high-efficiency solar cell and module technologies is underway to further enhance the product efficiency; 21% or higher cell efficiency is obtainable with PERC or IBC technology, and a gain of 3Wp or higher module output power is feasible with the multi-busbar technology. IBC production line with 30MW per year throughput has been successfully completed as a part of the 863 state key project objectives. In recent times, technology transfer of leading PV technologies such as N/P bifacial solar cell, MCCE black silicon, and directly grown silicon wafers have taken place.

Testing Center

The testing center consists of PV module reliability testing laboratory, physics and chemistry laboratory, and comprehensive management center. The center provides testing services in compliance with the latest photovoltaic testing standards, such as IEC and UL, to internal and external clients. Test categories include module reliability, PV materials’ thermal analysis, and physical & chemical properties, totaling 175 items. In 2016, the group established and reviewed in-house testing standards.

Administrative Office

The administrative office, otherwise known as office, consists of three groups - project management, training & PR, and patents & standards. The group is responsible for managing research collaboration programs with various academic institutions around the world, domestic government science and technology projects, intellectual properties, and relationships with internal and external stakeholders. In addition, the group provides administrative supports to all research groups within SKL PVST.
Chapter 2 Research Updates

- 2.1 Crystalline Silicon Solar Cell Material Research Center
- 2.2 Crystalline Silicon Solar Cell Research Center
- 2.3 PV Module & New Product Research Center
- 2.4 PV System Research Center
- 2.5 Equipment Research Center
2.1 Bulk lifetime of a silicon brick

Measurement of minority carrier lifetime involves optical excitation and signal detection. μ-PCD (Microwave Photoconductivity Decay) and QSSPC (Quasi Steady State Photoconductance) are common methods used as lifetime measurements. With μ-PCD, the pulse of an infrared semiconductor laser (904nm wavelength) generates free electron-hole pairs on an illuminated sample area, and the decaying conductivity can be monitored by the microwave reflectance detector. With QSSPC, the sample is illuminated with an IR-Pass filtered Xenon flash lamp while the photoconductance is measured simultaneously by an eddy current conductance sensor [1]. The measurement depth of QSSPC is approximately 3mm while that of μ-PCD is approximately 30μm. Since the dimensions of silicon brick, 156mm×156mm×360mm, is much deeper than the carrier injection depth and the effective carrier lifetime measurement is not affected by the wafer surface condition, the minority carrier lifetime estimated can be directly measured on the silicon brick.

As shown in Figure 1, the carrier lifetime alongside the crystal growth direction of silicon brick increases initially before peaking at approximately 15cm deep into the brick, then declines. The low carrier lifetime at the top is caused by the directional solidification of impurities during the crystal growth process, accompanied by the presence of dislocations and recombination centers.

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1 Background

There is a strong relationship between the efficiency of solar cell and its minority carrier lifetime. The minority carrier lifetime is mainly affected by impurities, dislocations, and grain boundaries where recombination thrives. Improving minority carrier lifetime of silicon will improve the efficiency of solar cell.

In order to obtain a high minority carrier lifetime of silicon, the silicon crystal growth process needs to be monitored to control the impurity content and the dislocation density. However, it is difficult to directly control the silicon crystal growth process. In 2016, a multi-crystalline silicon (mc-Si) wafer with a high minority carrier lifetime was successfully procured by employing homogeneous nucleation technology. Characterization of a high minority carrier lifetime of mc-Si was carried out for an in-depth analysis of high performance silicon crystal.

2 Characterization of high minority carrier lifetime silicon

2.1 Bulk lifetime of a silicon brick

Measurement of minority carrier lifetime involves optical excitation and signal detection. μ-PCD (Microwave Photoconductivity Decay) and QSSPC (Quasi Steady State Photoconductance) are common methods used as lifetime measurements. With μ-PCD, the pulse of an infrared semiconductor laser (904nm wavelength) generates free electron-hole pairs on an illuminated sample area, and the decaying conductivity can be monitored by the microwave reflectance detector. With QSSPC, the sample is illuminated with an IR-Pass filtered Xenon flash lamp while the photoconductance is measured simultaneously by an eddy current conductance sensor [1]. The measurement depth of QSSPC is approximately 3mm while that of μ-PCD is approximately 30μm. Since the dimensions of silicon brick, 156mm×156mm×360mm, is much deeper than the carrier injection depth and the effective carrier lifetime measurement is not affected by the wafer surface condition, the minority carrier lifetime estimated can be directly measured on the silicon brick.

As shown in Figure 1, the carrier lifetime alongside the crystal growth direction of silicon brick increases initially before peaking at approximately 15cm deep into the brick, then declines. The low carrier lifetime at the top is caused by the directional solidification of impurities during the crystal growth process, accompanied by the presence of dislocations and recombination centers.

Figure 1
The change of minority carrier lifetime alongside the crystal growth direction of silicon brick
2.2 PL imaging of silicon brick

The brick PL imaging equipment developed by BT Imaging Company is a fast, spatially resolved and sensitive measuring tool that could be employed to measure the whole cross-section of the silicon brick [2]. Photoluminescence of crystalline silicon is caused by radiative recombination of photo-excited electron–hole pairs. The radiative component of the recombination of excess charge carriers, \( \Delta n \), can be detected with a Si-CCD camera. Recombination centers in crystal could reduce electron–hole pairs, showing up as dark spots on a PL image.

The formation of dislocation during the crystal growth process, and carrier recombinations in the brick are clearly shown on the brick PL image. Figure 2 illustrates different PL images of (a) high carrier lifetime of a brick and (b) low carrier lifetime of a brick. The dislocation density of the high-lifetime brick is lower than that of the low-lifetime brick.

In addition, precise locations of the dislocation density and the impurity density can be obtained with a special calculation based on the PL imaging; the result is shown in Figure 3.

3. Measurement of a high minority carrier lifetime of wafer

3.1 Bulk lifetime of a wafer with high minority carrier lifetime

For as-cut silicon wafers, the effective carrier lifetime is largely limited by the cut surface of the wafer where dangling bonds can easily be introduced to. Usually, the defect density of the surface is higher than that of the bulk [3]. It is essential to minimize the surface recombination to get an effective carrier lifetime. The relationship between the effective carrier lifetime and the bulk carrier lifetime is as follows [4]:

\[
\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_{\text{bulk}}} + \frac{1}{\tau_{\text{surf}}} + \frac{1}{\tau_{\text{diff}}} \quad \text{(Equation 1)}
\]

\[
\tau_{\text{surf}} = \frac{W}{S} \quad \text{(Equation 2)}
\]

\[
\tau_{\text{diff}} = \frac{W^2}{2 \pi} \quad \text{(Equation 3)}
\]

where \( \tau_{\text{eff}} \) is the effective carrier lifetime, \( \tau_{\text{bulk}} \) is the bulk carrier lifetime, \( \tau_{\text{surf}} \) is the surface lifetime, \( \tau_{\text{diff}} \) is the diffusion lifetime, \( S \) is the surface recombination velocity (cm·s\(^{-1}\)) and \( W \) is the thickness of wafer (cm).

Conventionally, silicon wafer is passivated by AlOX and SiNX layers on both sides to get an effective carrier lifetime.

3.2 The effect of phosphorus diffusion gettering

The phosphorus diffusion process is not only a useful processing step to fabricate P-N junction for a P-type silicon substrate but also an effective way to reduce metal impurities in silicon [5]. The carrier lifetime of a gettered silicon wafer could be an effective indicator for its solar cell efficiency. Adjacent wafers in the silicon brick with high carrier lifetime are divided into two groups. Group1 is processed without gettering, and Group2 is processed with gettering. Results of the carrier lifetime of the two groups are shown in Figure 4. For a high carrier lifetime wafer, the minority carrier diffusion length is increased by gettering, and subsequent improvement of carrier lifetime [6]. In addition, the concentration of interstitial Fe declines from \( 3 \times 10^{10} \) to \( 1 \times 10^{10} \) cm\(^{-3}\) to a negligible value for a P-diffused silicon brick.

PL imaging is an effective, fast and informative tool, capable of presenting the carrier distribution in silicon wafers and the minority carrier lifetime. It is a high-precision and damage-free, quality control tool for as-cut mc-Si wafers prior to cell processing steps, widely used in photovoltaic industry [7]. PL images in Figure 5 show the distribution of excited non-equilibrium carrier concentration and minority carrier lifetime under varying illuminations. Minority carrier lifetime was measured using QSSPC. Images also show differences in grain sizes in mc-Si wafers - for wafers with the same surface passivation, the variance in grain sizes could be attributed to the Shockley Read Hall (SRH) recombination.

\[
\tau_{\text{eff}} = \frac{1}{\Delta \tau + \tau} \quad \text{(Equation 4)}
\]
A strong correlation between wafer minority carrier lifetime and non-equilibrium carrier concentration can be observed from images in Figure 5. Figure 6 shows the relationship between the minority carrier lifetime of high-lifetime Si wafers and the injection levels - a slight difference between the PL imaging calculation and the QSSPC measurement is due to the areal difference. The minority carrier lifetime initially rose as the injection level rose, however, it declined after peaking at $10^{15}$ cm$^{-3}$ injection level. At a lower injection level, a relatively lower lifetime is mainly attributed to SRH recombination. A decrease of minority carrier lifetime at high injection level is attributed to the Auger recombination. The recombination mechanism is complex in crystalline silicon. It correlates not only to high-metal impurity atoms but also to meta-stable defects caused by cross-linked impurities [9].

The minority lifetime in the low-recombination region of Si wafer has a weak correlation with the injection level. The graph in Figure 8 presents the correlation between the minority carrier lifetime and the injection level below $2 \times 10^{14}$ cm$^{-3}$. The minority carrier lifetime in the high-recombination region increased as more carriers were injected, however, the minority carrier lifetime in the low-recombination region remained constant as more carriers were injected.

The correlation between minority carrier lifetime and the injection level varied depending on the level of recombination. The recombination mechanism is complex in crystalline silicon. It correlates not only to high-metal impurity atoms but also to meta-stable defects caused by cross-linked impurities [9].

4. Minority carrier lifetime in silicon wafer and silicon brick

As a silicon brick gets sliced into wafers, an increasing level of defect density is introduced onto the wafer surface. Sliced wafers with varying levels of minority carrier lifetime were wafered and the minority carrier lifetime was measured. The graph in Figure 9 shows a positive correlation between the minority carrier lifetime in a silicon brick and the minority carrier lifetime in a wafer.

5. Conclusion and prospective

PL imaging is an effective characterization tool to measure a minority carrier lifetime in crystalline silicon. The minority carrier lifetime is a good indicator of the crystalline silicon quality, and the finished solar cell efficiency. It is also a reliable reference to monitor and optimize cell processing steps. In this paper, a precise characterization technique to measure the bulk minority carrier lifetime in the silicon brick and the wafer, and the factors that affect minority carrier lifetime in silicon were explored.

Trina solar has developed an innovative product, T1 by optimizing the crystal growth process. T1, a higher quality crystalline silicon is one of the key steps to improve the solar cell efficiency at Trina Solar. The bulk carrier lifetime in T1 could reach up to 1ms – 2ms which is one of the highest in the industry.

References

Hetero-seed-assisted growth of high-performance multi-crystalline silicon in directional solidification

Changhao Yin

Over the past years, due to its cost-effectiveness, the high-performance multi-crystalline silicon (HP mc-Si) ingots grown in directional solidification has been the main material for photovoltaic (PV) devices. The seedling process is considered to be the key step in the growth of HP mc-Si which determines both the initial grain shape distribution and the dislocation density level of silicon crystal. The heterogeneous seed-assisted crystal growth (hetero-seeding) technology is becoming the promising casting method for PV silicon ingots for its simple operation, short process cycle, and high ingot casting yield. In this paper, we review the research progress of hetero-seeding technology for HP mc-Si growth. Fused silica particles have been widely used as a hetero-seed as its resultant solar cell conversion efficiency can be as high as that obtainable from the homogeneous seeding (homo-seeding) growth. However, some defects in fused silica, such as the oxygen contamination, limit the quality of solar cell. We propose SiC and Al2O3 to be used as the seeding material instead of fused silica.

1. Background of seed assisted HP mc-Si

Since its conception, the crystalline silicon grown by directional solidification has undergone three main stages of development: 1) the conventional casting multi-crystalline silicon (mc-Si) with no given seeds, 2) the quasi-single-crystalline silicon (QSC-Si) with mono-crystalline silicon bricks or blocks as seeds, and 3) the high-performance multi-crystalline silicon (HP mc-Si) with polycrystalline or multi-crystalline silicon (silicon powder, particles or fragments) as seeds. The cell conversion efficiency improved using both the QSC casting method and the HP casting method – the QSC casting method decreased the grain boundary fractions while the HP casting method reduced dislocation densities in the crystal. However, the QSC casting method, limited by the single-crystal area ratio and the production cost, was not ideal for mass production. Thus, the HP casting method, due to its high cost-effectiveness, has now been widely adopted in the industry.

It is well recognized that cultivating the columnar grains in parallel growth directions is an effective way to suppress the generation and propagation of dislocations, which would be a great breakthrough for improving the quality of mc-Si [6, 7, 9, 11]. HP mc-Si was developed based on a low dislocation density crystal grown by the seed-assisted method. The seeding step, which determines the initial grain shape distribution, is quite essential for the growth of columnar grains. Both homoseeding and hetero-seeding methods have been developed to assist the growth of columnar grains which are considered capable of absorbing stress [6, 7, 9]. Due to its simple operation, a short processing cycle and a high ingot casting yield, the hetero-seeding is expected to be a promising seeding method.

Usually, the homo-seeding displays good seeding effect, however, the melting process must be precisely controlled to make sure that enough silicon seeds are preserved and the melting/growth fronts are as flat as possible. In contrast, since no silicon seeds need to be preserved, the hetero-seeding is more suitable to rapid melting processes. The innate distinction between the hetero-seeding and the homo-seeding is whether the nucleation process is involved during the directional solidification. The nucleation refers to the initial stage of crystallization: under a certain degree of undercooling with temperature and concentration fluctuations, some atoms of the melt gather and reach to a critical size and become solid particles. The surrounding atoms then could pile up to further reduce the free energy of these atoms that formed the nuclei. For the homo-seeding process, the silicon crystal (the seeds) always exists during melting process, and the silicon crystal epitaxially grow into a complete ingot in the subsequent directional solidification steps without going through the nucleation process. For the hetero-seeding process, since all silicon feedstock is melted before crystallization, the nucleation process is inevitable. A controlled nucleation process is quite important for the subsequent crystal growth of columnar grains.

The architecture of the advanced seeding layer, the control of growth fronts and the degree of undercooling enable the efficiency of the solar cell obtained from the hetero-seeding method to be as high as that obtained from the homo-seeding method. Therefore, the hetero-seeding-assisted help the high-performance multi-crystalline silicon grows is gaining increasing attention. However, compared to the homo-seeding method, two intrinsic characteristics of the hetero-seeding method, the instability of seeding effect and the sticking risk, are considered the two biggest challenges of the hetero-seeding method. Table 1 shows the mainstream homo- and hetero-seeding materials used for growth of HP mc-Si in directional solidification. The seeding mechanisms and the seeding effects with different feed materials will be discussed in detail in the following sections.

2. Seeding mechanism of hetero-seeding

According to recent studies [12-14], uniform columnar grains could be obtained by optimizing the types and the particle sizes of the seed, the thermal field structure and the crystal growth process using hetero-seeding directional solidification system. Hetero-seeding structures could be divided into two groups: the bared-particles seeding (bp-seeding) and the covered-particles seeding (cp-seeding).

The seeding mechanism of bp-seeding is shown in Figure 1. The seeding process could be described in four steps: (a) the melting of silicon feedstock, (b) seeds protrude through the Si3N4 coating and are etched by Si melt, (c) Si crystal nucleates at the seeds and epitaxially grows, (d) seeds detach from Si ingot. Figure 2 shows the visual morphology of a seeding layer of bp-seeding before and after casting. Step (a) and (b) could be combined to shorten the process cycle in real production, thus, before loading, the seeding layer is treated to make sure tips of seeding particles are exposed through the Si3N4 coating.

The seeding mechanism of cp-seeding is shown in Figure 3. The seeding process could be described in three steps: (a) melting and penetrating, (b) nucleation and growth, (c) detaching. Different from the bp-seeding, the seeds of cp-seeding are covered by the Si3N4 coating during the whole casting process. The Si3N4 coating is thick for tips of seeding particles to protrude through it. Silicon melt or silicon vapor permeates through the Si3N4 coating and nucleates at seeding particles. Figure 4 shows the visual morphology of a seeding layer with covered-particles as seeds, before and after casting.
Both bp-seeding and cp-seeding could be used to form uniform columnar grains. The advantage of bp-seeding is that the silicon melt could easily contact with seeds, therefore, the heating and melting cycles could be shortened, while the cp-seeding needs more holding time after the melting to ensure that enough silicon penetrates through the Si₃N₄ coating and nucleates. However, due to a direct contact between the melt and seeds leading to a direct contact between the silicon ingot and seeds, the bp-seeding is usually associated with a high risk of sticking.

3. Seeding materials for hetero-seeding

In order to obtain a better seeding effect, types of seeding materials have been investigated. It is necessary to consider following factors for seeding materials: the wettability between seeds and the silicon melt, the melting point of seeds and the silicon melt, essential for stable seeding effect. SiC seeds are void of oxygen contamination and spincal Al₂O₃ seeds could be arranged uniformly onto the silica crucible to form a more textured seeding layer. Stable and consistent seeding results could be expected by optimizing hetero-seeds’ types and structures, and when coupled with optimized thermal field, a significantly improved solar cell conversion efficiency as high as that from the homo-seeding method could be obtained.

4. Thermal field optimization

For silicon crystal growth, a successful seeding is a prereq- uisite for growing columnar grains. The subsequent directional solidification is also important to the crystal quality [17, 18]. Figure 5 shows the direction of grains and the dislocation distribution (by brick PL) in HP mc-Si bricks grown in different thermal fields. It can be seen that in regions where grains bend and/or intersect, the level of dislocation density is very high. The slanting in a grain is caused mainly by the thermal field structure and the growth process. Optimizing the thermal field structure and the growth process is the key to improving the crystal quality of silicon.

5. Summary

Hetero-seed-assisted growth of HP mc-Si is expected to be the most common methodology for silicon ingot growth due to its advantages of highly-cost-effectiveness and simple opera- tion. Fused silica has been used as a mature hetero-seeding material to grow the HP mc-Si whose resulting cell conversion efficiency could be as high as that of the one grown with homo-seeding method. SiC and Al₂O₃ are two potential candidates for a hetero-seeding material as both have good wettability to silicon melt, essential for stable seeding effect. SiC seeds are void of oxygen contamination and spincal Al₂O₃ seeds could be arranged uniformly onto the silica crucible to form a more textured seeding layer. Stable and consistent seeding results could be expected by optimizing hetero-seeds’ types and structures, and when coupled with optimized thermal field, a significantly improved solar cell conversion efficiency as high as that from the homo-seeding method could be obtained.

References


Figure 5
Infrared and brick PL maps of HP mc-Si bricks within different thermal fields. a. infrared map of brick with tilt grains. b. brick PL map of brick with tilt grains, dislocation density ratio<4.5%. c. infrared map of brick with vertical grains . d. brick PL map of brick with vertical grains, dislocation density ratio>5%

Table 1 Homo- and hetero-seeding materials used for the HP mc-Si growth in directional solidification.

<table>
<thead>
<tr>
<th>Seeding types</th>
<th>Seeding method</th>
<th>Contact angle (°)</th>
<th>Seed sp. effect</th>
<th>Silicon melt zone/half-batch (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homo-seeding</td>
<td>Si</td>
<td>yes</td>
<td>low</td>
<td>stable</td>
</tr>
<tr>
<td>Hetero-seeding</td>
<td>SiO₂ (purity)</td>
<td>no</td>
<td>&gt;90</td>
<td>middling</td>
</tr>
<tr>
<td></td>
<td>SiC (p-phase)</td>
<td>no</td>
<td>&gt;91</td>
<td>unstable</td>
</tr>
<tr>
<td></td>
<td>Al₂O₃</td>
<td>no</td>
<td>&lt;90</td>
<td>unstable</td>
</tr>
</tbody>
</table>

At present, the fused silica is widely used as the seeding material to assist the growth of HP mc-Si in industry, mainly because the purity of fused silica could be easily controlled and the silica particles show moderate wettability to silicon melt. At present, the fused silica is widely used as the seeding material to assist the growth of HP mc-Si in industry, mainly because the purity of fused silica could be easily controlled and the silica particles show moderate wettability to silicon melt.

There are some side effects when using fused silica as the seeding material. The biggest issue is the oxygen contamination of the silicon crystal which is considered to be the main reason for light-induced degradation in a solar cell. Part of fused silica would be dissolved into molten silicon which would result in a high concentration of oxygen in the silicon ingot, especially at the bottom.

In addition to fused silica particles, silicon carbide (SiC) particles have also been tried as a seeding material. Since SiC shows better wettability to the silicon melt (=90°) than fused silica (=90°) [15] and hardly causes the oxygen contamination, SiC is considered to be a promising seeding material. However, controlling the purity may be the biggest challenge for SiC as a seeding material. Al₂O₃ is another candidate for a seeding material. Since Al₂O₃ can be processed into perfect spherical particles, Al₂O₃ seeds could be arranged uniformly onto the silica crucible to form a more textured seeding layer, which is expected to benefit the silicon grain size distribution. Also, since the element Al is an acceptor impurity in silicon crystal, Al₂O₃ seeds may help reduce the resistivity at the bottom of the ingot.

Table 2 Homo- and hetero-seeding materials used for the HP mc-Si growth in directional solidification.
2.2 Crystalline Silicon Solar Cell Research Center

R&D and industrialization of P-type PERC solar cells

Weiwei Deng, Feng Ye, Ruimin Liu, Yunpeng Li, Haiyan Chen, Yifeng Chen, Yang Yang

In 2016, industrial processes for the p-type Si PERC solar cell were optimized, mainly on the surface passivation on the front and the rear of solar cells, emitter doping, and metallization. Transferring these key technologies and the solution of key issues to the manufacturing line was the main focus. As a result, the average efficiency of solar cells from the manufacturing line has gone up - above 21.1% for the mono-Si and 20.1% for the multi-Si from the Golden Line. The maximum efficiency for the mono-Si PERC from the manufacturing line was 22.22%. World record cell efficiencies were also achieved on a 6-inch mono-Si substrate and a 6-inch multi-Si substrate, reaching up to 22.61% and 21.25%, respectively. Both records were independently certified by Fraunhofer ISE CalLab.

1. Background

The P-type Si PERC solar cell has received special attention due to its cost-effectiveness. Compared with conventional BSF solar cells, the rear surface recombination velocity is significantly lower due to the introduction of passivated dielectric layers. The resulting Voc and Isc have been promoted heavily, especially for the diffusion process optimization. Selective emitter was used for our PERC solar cell where the lightly diffused area was fabricated by etching off the heavily diffused area. Since the lightly diffused area takes up more than 80% of the wafer area, the diffusion concentration curve is very important for the saturation current density, J0. The optimized diffusion curve has a lower surface diffusion concentration and a deeper junction depth as illustrated in Figure 3 with almost the same sheet resistance as the non-optimized sample. The saturation current density, J0, decreased from 105 A/cm² to below 60 A/cm² as recombination losses were eliminated. The surface diffusion concentration, as low as 3E20cm⁻³, is capable of ensuring a good contact with the solar cell front.

2.2 Metallization process optimization

Screen printing technology is still used on the mass production line. For the front-side printing, a better aspect ratio of front finger and a lower J0 under metal can be obtained by optimizing the mesh number of the printing plate and the thickness of the emulsion film - to increase Voc. On the rear side, by optimizing the Al-Si paste, J0 decreased to approximately 420 A/cm² which resulted in an increase of Voc.

In 2016, the world record cell efficiency of industrial mono-Si PERC cell was broken again by optimizing processing steps. The mono-Si PERC cell efficiency reached up to 22.61% on a 5-inch p-type mono wafer. It was certified by Fraunhofer ISE CalLab and was the third mono-Si PERC cell world record for SKL PVST since 2014. Figure 5 shows the IV curve and corresponding electrical parameters for the champion mono-Si PERC solar cell. Figure 6 shows IQE, EQE and the reflectance for the champion Si PERC cell.

2.1 Emitter optimization

Emitter optimization is crucial for improving the cell efficiency, especially for the diffusion process optimization. Selective emitter was used for our PERC solar cell where the lightly diffused area was fabricated by etching off the heavily diffused area. Since the lightly diffused area takes up more than 80% of the wafer area, the diffusion concentration curve is very important for the saturation current density, J0.

Diffusion area ratio design is also very important to ensure high cell efficiency. After the optimization of inkjet masking and metallization, J0cell, J0rear, and J0total, which deteriorate the cell efficiency could be improved by collocating the ratio of different areas. Figure 4 shows an increase in Voc, as the diffusion area gets smaller.

Table 1. Electrical parameters for the champion mono-Si PERC solar cell

<table>
<thead>
<tr>
<th>Voc(mV)</th>
<th>Jsc(mA/cm²)</th>
<th>FF(%)</th>
<th>η(%)</th>
<th>Area(cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>684.4 (±0.77)</td>
<td>40.54 (±0.53)</td>
<td>81.49 (±0.45)</td>
<td>22.61 (±0.24)</td>
<td>2322</td>
</tr>
<tr>
<td>678.4 (±2.3)</td>
<td>40.77 (±0.40)</td>
<td>81.82 (±0.40)</td>
<td>22.81 (±0.24)</td>
<td>2342</td>
</tr>
</tbody>
</table>

Figure 1: Phosphorus Diffusion ECV curve and corresponding J0

- Figure 2: Variation of Voc against the width of heavily diffused area
- Figure 3: IV curve and corresponding electrical parameters for the champion mono-Si PERC solar cell
- Table 1: Electrical parameters for the champion mono-Si PERC solar cell

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*Images and diagrams are not included in the text.*
Currently, independently developed p-type mono-Si and multi-Si solar cells have been steadily mass-manufactured. Our future research direction focuses on the cost-effectiveness. Research has been carried out in the Golden Line on commercializing P-type PERC solar cells including the management of the cleanliness of workshops, the equipment updates that have gradually resolved the stability issue in the mass production line, and the optimization of silicon wafers and processing steps. Through optimization, the mono-Si and the multi-Si cell efficiencies have increased from 20.4% and 18.8% to 21.2% and 20.16%, respectively. Corresponding modules’ efficiencies have reached 300Wp and 285Wp, respectively.

3. Industrialization of PERC solar cell

Currently, independently developed p-type mono-Si and multi-Si solar cells have been steadily mass-manufactured. Our future research direction focuses on the cost-effectiveness. Research has been carried out in the Golden Line on commercializing P-type PERC solar cells including the management of the cleanliness of workshops, the equipment updates that have gradually resolved the stability issue in the mass production line, and the optimization of silicon wafers and processing steps. Through optimization, the mono-Si and the multi-Si cell efficiencies have increased from 20.4% and 18.8% to 21.2% and 20.16%, respectively. Corresponding modules’ efficiencies have reached 300Wp and 285Wp, respectively.

3.2 Contamination control

Diffusion optimization is very important for PERC solar cells. In Figure 8, the saturation current density, $J_0$, decreased from 190 fA/cm$^2$ to 140 fA/cm$^2$ after the diffusion process was optimized. The cell efficiency gain was approximately 0.1%.

3.3 Rear pattern optimization

Rear local BSF optimization is very important for cell efficiency, as well as for module’s mechanical loading capacity. Optimization of the laser pattern, the Ag/Al paste and the Al paste was performed which resulted in a corresponding efficiency gain of approximately 0.07%, 0.17% and 0.12%.

4. R&D of industrial bifacial PERC solar cell

A P-type bifacial PERC cell has characteristics of a conventional high-efficiency single PN-junction PERC solar cell and as the name suggests, can generate electricity on both front and rear sides. Post processing optimization, the front cell efficiency was approximately 21.2%, and the rear cell efficiency was approximately 10%. The reliability tests are currently in progress. The IV curve parameters of a pilot batch cell are shown in Table 4.

5. Summary

The main drive for the current R&D in PV is to improve the efficiency while continuing on the effort to reduce the manufacturing cost. PERC solar cell has a large potential in this regard its manufacturing cost is lower compared with other advanced solar cell options. We hope to reach the goal of high-efficiency, low-cost solar cell production through PERC R&D programs.
High-efficiency N-PERT solar cells and industrialization

Shengzhao Yuan, Yun Sheng, Ziyang Wang, Yanfeng Cui, Chengfa Liu, Daming Chen, Yifeng Chen, Yang Yang

N-PERT solar cells are developed by optimizing the passivation (surface and bulk passivation) and the metallization (plating and evaporation). 22.4% and 21.4% (measured at SKL PVST) have been obtained on a mono-facial structure and a bifacial structure respectively. A pilot production of bifacial solar cells is currently being implemented in the Gold Line, with an aim of achieving an average front cell efficiency of 21.2% and an average rear cell efficiency of 20.5%.

1. Background

The N-type solar cell has caught the attention of the industry and institutions due to its high bulk lifetime and free-of-LID characteristic. During the past decade, the development of N-PERT solar cell has had a remarkable advancement. IMEC reported 22.7% efficiency with a rear-emitter cell structure. In 2002, Zhao at UNSW reported that 21.9% efficiency was attained with a front-emitter cell structure, two-side diffusion and passivation [1]. 22.7% efficiency with a rear-emitter cell structure was reported subsequently [2]. In 2009, Fraunhofer laboratory reported 23.4% efficiency on a 4 cm² PERL cell [3]. Then in 2010, Fraunhofer laboratory reported 23.9% efficiency with a front-emitter cell structure, Al₂O₃ passivation and Al/Ti/Pd/Ag metallization [4]. This 23.9% efficiency is the highest recorded efficiency for the PERL cell. The R&D progress of N-type bifacial solar cells is announced frequently. At EUPVSEC in 2015, IMEC published the paper on the bifacial solar cell with a Ni/Cu plated rear emitter [5]. 22.5% efficiency was attained on the 6-inch wafer with resistivity of 5 Ω cm⁻¹. In 2016, the efficiency improved to 22.6%.

2. N-PERT solar cells

State Key Laboratory for PV Science and Technology (SKL PVST) began the front-emitter N-PERT solar cell R&D program in 2014. The illustration of the cell structure is shown below in Figure 1. In 2015, 21.98% efficiency on a 5-inch wafer with resistivity of 3 Ω cm⁻¹ was certified by Fraunhofer. In 2016, 22.2% efficiency was achieved with Vₜ of 688.3 mV [7]. Recently, 22.4% efficiency (measured at SKL PVST) was attained on a 6-inch wafer with 30μm-wide, Ni/Cu/Ag plated fingers – SEM image of the plated finger and the IV curve are shown in Figure 2 and Figure 3.
The efficiency of N-type bifacial solar cells improved from 20.4% to 21.4% in 2016 by optimizing the selective BSF and the bulk lifetime (Figure 7).

The efficiency distribution of N-type bifacial solar cells in the pilot line is shown in Figure 8. The average efficiency is 21.2% and the maximum is 21.7%.

3. Summary

The outlook on industrialization of N-PERT solar cells is promising at SKL PVST. In particular, N-type bifacial solar cells are free of LID and produce lower LCOE (Levelized Cost of Electricity) than conventional P-type solar cells. However, currently available commercial N-type solar cells do not show clear benefits when compared with commercial P-type solar cells, except in special applications, due to high-cost N-type wafers and complicated processing steps. With continued process optimization and efforts to reduce cost, we expect to commercialise high-efficiency and high-reliability N-type solar cells in near future.

References


With excellent electrical performance and visual aesthetics, IBC cell has become increasingly popular and is considered to be one of the most promising high efficiency solar cells suitable for commercialisation. Its application is extensive ranging from terrestrial power plants to car rooftops. The process and the structure of the IBC cell were further optimized in 2016 and the highest industrialized IBC cell efficiency of 23% was obtained on a 6-inch c-Si substrate.

1. Background

Interdigitated Back-Contact (IBC) solar cell is a silicon based solar cell with both emitter and back contacts fabricated on the rear side in an interdigitated grid format as shown in Figure 1. The concept was introduced in 1975 by Lammert and Schwartz, and after nearly 40 years’ development, the IBC solar cell conversion efficiency now reaches up to 25.2% under STC [3], the highest conversion efficiency of a single PN junction silicon solar cell. Compared with a conventional solar cell, the IBC cell requires a higher quality wafer and a more sophisticated process flow which remain to be the main hindrance to a large-scale adoption.

2. IBC solar cell research progress

Recorded conversion efficiency of 23.5%, certified by Japan Electrical & Environment Technology Laboratories (JET) with 23.5% IBC Cell (certified by JET) and Panasonic Corporation [9] reported 25.1% and 25.6%, respectively, on a HBC cell, a combination of IBC and HJT technologies. KANENKA Corporation and NEDO research institute announced jointly the conversion efficiency of 26.33% on a 180cm² silicon wafer in September, 2016. This was the world record at the time for the HBC solar cell. KANENKA and NEDO also successfully fabricated a HBC module by interconnecting 108 HBC cells. The total area was 13177cm², and the module conversion efficiency was 24.37% which broke the record efficiency of 24.1% set by SunPower.

Table 1. Research progress of IBC cell technology

<table>
<thead>
<tr>
<th>Corporation/ research institute</th>
<th>Cell size</th>
<th>Type</th>
<th>Key technology</th>
<th>Highest efficiency</th>
<th>Reported year</th>
</tr>
</thead>
<tbody>
<tr>
<td>SunPower</td>
<td>5”</td>
<td>IBC</td>
<td>Printing</td>
<td>25.4%</td>
<td>2015</td>
</tr>
<tr>
<td>Sharp</td>
<td>5” or 4”</td>
<td>HBC</td>
<td>Screen-printed</td>
<td>25.1%</td>
<td>2014</td>
</tr>
<tr>
<td>Panasonic</td>
<td>5” or 4”</td>
<td>HBC</td>
<td>Screen-printed</td>
<td>25.0%</td>
<td>2014</td>
</tr>
<tr>
<td>Kaneka</td>
<td>180 cm²</td>
<td>HBC</td>
<td></td>
<td>26.33%</td>
<td>2015</td>
</tr>
<tr>
<td>AKEI</td>
<td>4 cm²</td>
<td>IBC</td>
<td>Lithography</td>
<td>24.4%</td>
<td>2014</td>
</tr>
<tr>
<td>Fraunhofer ISC</td>
<td>4 cm²</td>
<td>IBC</td>
<td>Evaporation</td>
<td>23.0%</td>
<td>2011</td>
</tr>
<tr>
<td>ISFH</td>
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<td>IBC</td>
<td>Evaporation</td>
<td>23.1%</td>
<td>2011</td>
</tr>
<tr>
<td>IMEC</td>
<td>4 cm²</td>
<td>IBC</td>
<td>Evaporation</td>
<td>23.3%</td>
<td>2011</td>
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<tr>
<td>Konidere ISC</td>
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<td>IBC</td>
<td>Screen-printed</td>
<td>25.3%</td>
<td>2012</td>
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<tr>
<td>Bosch</td>
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<td>IBC</td>
<td>Iron-implantation</td>
<td>22.1%</td>
<td>2013</td>
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<tr>
<td>Samsung</td>
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<td>IBC</td>
<td>Iron-implantation</td>
<td>22.4%</td>
<td>2012</td>
</tr>
<tr>
<td>Trina solar</td>
<td>5”</td>
<td>IBC</td>
<td>Screen-printed</td>
<td>25.3%</td>
<td>2015</td>
</tr>
</tbody>
</table>

Table 2. Cell efficiency of IBC cell pilot line

<table>
<thead>
<tr>
<th>Area (cm²)</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (V)</th>
<th>FF (%)</th>
<th>Eff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>42.6</td>
<td>0.87</td>
<td>68.9</td>
<td>23.3</td>
</tr>
<tr>
<td>Champions in pilot line</td>
<td>42.0</td>
<td>0.88</td>
<td>68.9</td>
<td>23.3</td>
</tr>
<tr>
<td>Best cell with small contacts</td>
<td>42.6</td>
<td>0.86</td>
<td>68.9</td>
<td>23.3</td>
</tr>
</tbody>
</table>

*The cell IV-curves were independently measured at Japan Electrical Safety & Environment Technology Laboratories (JET)

In May, 2016, a new IBC cell efficiency record of 34.5% under 1 sun illumination was attained by UNSW and NREL. The record was set by Dr. Mark Keevers and Professor Martin Green, a senior research fellow and the director, respectively, of UNSW’ s Australian Centre of Advanced Photovoltaics. A 28cm² mini-module embedded in a prism was employed to extract the maximum energy from the sunlight. It did so by splitting incoming rays into four bands, using a hybrid four-junction receiver to squeeze even more electricity from each beam of the sunlight. The mini module had ‘Trina Solar’ s IBC cell on one side of the glass prism, with a triple-junction solar cell on the other, as shown in Figure 6. The configuration can promote the conversion efficiency to 34.5%.

23% IBC Cell (certified by JET)

Figure 5

Cell efficiency distribution with an average efficiency of 23%
The reliability of double glass IBC modules was evaluated. Tests that are more stringent than those in IEC 61215, for example DH3000 and TC600, were conducted and the module power loss was less than 2%. The Cu foil coated module was subjected to PID test under 1000V positive- and negative-bias and the module power loss was also less than 2%. The test results shown in Figure 7 verify that the IBC module is more reliable than the conventional PV module.

High efficiency modules such as IBC modules are a great option for systems with limited installation space. A typical example is the high-end application such as an aircraft (Solar Impulse 2) and a solar racing car. This year, as part of a collaboration with Osaka Sangyo University (OSU), 78mm x 78mm, independently developed new high efficiency IBC cells were provided which fitted very nicely over the chassis of OSU’s racing car named OSU-Module-S. This year’s IBC cells had an improved optical optimization and weighed 1.3Kg/m², one tenth of the conventional module weight per square meter. As a result, the IBC module chassis generated 3% more power than the one procured in 2015 on the same given area, and the car maintained an average speed of 80km/hr even on cloudy days with relatively low irradiance. OSU-Module-S won the Dream class division in this year’s race (Figure 9).

Another typical area of application for IBC modules is on the rooftop space of an automobile such as a bus or a family car. An independently developed double glass IBC module with a curvature to fit onto a car roof is shown in Figure 9. Trina Solar’s IBC cells and modules have been selected to be used on EVs and hybrid cars by reputable automobile companies.

11 patents have been applied for by the independently developed SKL PVST’s IBC cell - 8 invention patents and 3 utility patents. One of invention patents titled “The method of IBC solar cell” (No.201210141633.5) won the 9th Jiangsu Patent Golden Award and the 18th China Patent Excellence Award.

4. Summary

IBC cell is one of the most promising high-efficiency solar cells with an e ext key step in the IBC R&D program.

References


Perovskite solar cells
Yun Sheng, Lei Wang, Yifeng Chen, Taoyun Xiao, Li Yin

The development of perovskite solar cell technology continues to advance. The works on material synthesis, device architecture, reliability, measurement and optoelectronic application are highly attractive. The State Key Laboratory of Photovoltaic Science and Technology (SKL PVST) collaborates with universities and academic institutes to investigate perovskite solar cell’s applications, testing methodologies and the technology standardization. This year, materials, device and performance measurement have been systematized at SKL PVST. In this paper, two types of perovskite solar cells, a mesoscopic structure and a regular planar structure, fabricated by one-step spin-coating method are being presented including their electrical properties and reliability measurements. The standardization of the current-voltage measurement method in progress is also reported.

1. Background
Since hybrid organic-inorganic halide perovskites served as an active absorber in mesoporous thin-film solar cells in 2009, perovskite solar cells (PSCs) have attracted great attentions from academics and industries [1]. PSCs exhibit excellent optical and electrical properties, and flexible fabrication. In the past seven years, researchers focused on the device architecture and innovative ways to grow the perovskite film, and discovered PCS-related mechanisms. The conversion efficiency continues to ascend - the latest efficiency of thin-film, and discovered PCS-related mechanisms. The conversion efficiency continues to ascend - the latest efficiency of thin-film, and discovered PCS-related mechanisms. The conversion efficiency continues to ascend - the latest efficiency of thin-film, and discovered PCS-related mechanisms. The conversion efficiency continues to ascend - the latest efficiency of thin-film, and discovered PCS-related mechanisms. The conversion efficiency continues to ascend - the latest efficiency of thin-film, and discovered PCS-related mechanisms. The conversion efficiency continues to ascend - the latest efficiency of thin-film, and discovered PCS-related mechanisms.

2. Research Contents
2.1 Film fabrication of perovskite solar cells
The synthesis of high quality perovskites and film fabrication are the main objectives of the perovskite cell research. Progressing from the solution method and the co-evaporation method, the vapor-assisted solution process and the intramolecular exchange have been proposed [3, 5]. In more recent intramolecular exchange technique, Woon et al. utilized the affinity difference between formamidinium iodide (FAI) and dimethylsulfoxide (DMSO) towards lead iodide (PbI2). This process, the group fabricated perovskite cells with efficiency up to 20.2%. Classic organic methylammonium (MA) and formamidinium (FA) based on lead halide perovskites have exhibited excellent photovoltaic properties, despite a low degree of crystallization and mobility, poor thermal stability and lead hazarousness. In recent years, completely inorganic perovskites became a popular choice for PSCs. Traditional ferroelectric such as BaTiO3 and Pb(Zr, Ti)O3, a type of inorganic perovskite materials, has large forbidden gaps which result in a low conversion efficiency [7]. Another completely inorganic no-lead perovskite, CsSnI3, has been reported broadly. In this structure, organic cation is replaced by inorganic Cs, and heavy metal Pb is substituted by the same group element, Sn. CsSnI3 is a p-type semiconductor with a band gap of 1.3 eV and delivers high current density due to its relatively high light absorption coefficient (~104 cm-1) and low exciton binding energy (~18 meV) [8-10]. Despite these promising features, CsSnI3 perovskite cells have instability problems due to self-oxidation of Sn2+ to Sn4+ [11]. Furthermore, Sn based perovskite should be approached with great caution as SnI3 is highly unstable in air, and can release strong acid, HI [12]. Therefore, there is still much work to be done on obtaining highly efficient and environment friendly perovskite materials. SKL PVST has set up an apparatus such as high vacuum deposition system, and low oxygen/water glove box, in order to carry out the preliminary study on perovskite materials synthesis and cell device construction.

2.2 Device Architecture
The device architecture of PSCs is diverse. The three main architectures include mesoscopic structure, regular planar structure and inverted planar structure, as shown in Figure 1. The mesoscopic structure derives from dye-sensitized solar cells which commonly has a mesoporous TiO2 layer as the scaffold. Many high efficiency results are obtained based on this architecture, for example, 20.1% and 20.8% reported by Seok’s and Gratzel’s groups respectively [6, 13]. The regular planar structure consists of an electron transport layer (ETL), a perovskite layer and a hole transport layer (HTL), without mesoscopic scaffolds - 19.3% efficiency is obtained on this architecture [5]. The inverted planar structure consists of an electron transport layer (ETL), a perovskite layer and a hole transport layer (HTL), which is similar to organic solar cells. The direction of the carrier transport in the inverted planar structure is opposite to the other two structures - 15% efficiency is obtained on a 1 cm² device [8]. Although the mesoscopic structure results in higher efficiency, the regular and inverse planar architectures are more suitable for low-temperature processes - the winning device architecture is not yet confirmed. This year, we have investigated PSCs with mesoscopic structure and regular planar architecture (Figure 2). Fabrication processes have been optimized to get high-quality and homogeneous thin-films.

2.3 Current-voltage (I-V) Measurement
The measurement method for electrical performance of PSCs requires regulation. The transient effects of PSCs induce I-V hysteresis and impact performance evaluation. The cause for transient behaviors such as ion immigration, carrier trapping/detrapping, interfacial accumulation, and chemical degradation are being investigated but need further insights. Several strategies, such as optimized setting of voltage sweep conditions, steady-state testing, incident photon-to-electron conversion efficiency (IPCE), to improve the I-V measurement have been reported [14]. Additionally, conditioning/preconditioning, apparatuses, sample defining and statistic methods all need improvements. This year, at SKL PVST, a specialized system to measure the electrical performance of PSCs has been set up which includes a solar simulator, an isothermal probe stage and a SMU. The voltage sweep direction, rate and pre-light soaking were investigated. Fabrication processes, device architectures and degradation have also been examined.
2.4 Reliability Testing

The reliability of PSCs is still a critical issue. Due to the weak chemical bonding, the perovskites are susceptible to decompose under a high-temperature and humid environment. Reactions in organic thin-films and at the interface also impact the reliability. Several studies deduce the improvement of PSC reliability [15-17]. For example, replacing part of the CaF₂ in CH₃NH₃PbI₃ with SCN- can enhance the moisture tolerance of the resulting perovskite material; a crystal crosslinking can be applied to improve device stability; device reliability can be further improved by using the inorganic HTL. In indoor environment testing, we investigated the reliability of the PSCs with and without an encapsulation. The performance variations under high-temperature and humidity are recorded using an environmental chamber. The efficiency of PSC without an encapsulation degrades less than 10% under 85°C and 21% RH for 10 hours (Figure 4). The efficiency of PSC with an encapsulation degrades less than 10% under both 20 thermal cycles or 40 DH hours [Figure 4]. The reliability of present PSCs is not comparable to commercialized PV technologies such as c-Si solar cells. Nevertheless, an improvement in reliability can be expected in future.

The potential application of PSCs is extensive. Thanks to the high and tunable energy bandgap of ABX₃ perovskites, a tandem solar cell with perovskite materials is a highly appealing solar cell device structure. Such device structure includes four-terminal, two-terminal and all-perovskite tandem solar cell structures. CH₃NH₃PbI₃ perovskite solar cell mechanically stacked on c-Si solar cell and CIGS solar cell resulted in an efficiency of 13% and 18.6% respectively [18]. EPFL reports 21.2% efficiency for the perovskite/HIT solar cell, fabricated with low temperature processes on a device area of 0.17 cm² of which the top sub-cell has 14.5% efficiency [19]. All perovskite tandem solar cell of MAPbBr₃/MAPbI₃ produced 2.2V of an open circuit voltage and 10.4% conversion efficiency [20]. Semitransparent and bendable solar cells are also interesting. Photodetectors and light-emitting diodes are also the optoelectronic application of perovskites.

3. Summary and Prospectives

Perovskite solar cell technology will continue to advance. High-efficiency, high-reliability, large-area fabrication, lead-free, and low-cost are the key ingredients to forward industrialization. A standardized measurement method is necessary and meaningful to accurately evaluate the performance. Several institutes are promoting the industrialization and application of PSCs. Oxford PV received the sustaining insurances in the advanced field of PSCs. Dyesol announced the signing of an co-operation letter of intent with CSIRO. SKL PVST collaborates with universities and academic institutes to research PSCs with a focus on the application and the testing methodologies and the standardization. This year, materials, device and performance measurement have been systematized at SKL PVST. Two types of perovskite solar cells, a mesoscopic structure and a regular planar structure, fabricated by one-step spin-coating method were investigated including their electrical properties and reliability measurements. The standardization of the current-voltage measurement method is in progress. In future, a greater collaboration either among the research institutes or among the institutions and the companies would be beneficial to the development of the perovskite solar cell application.

References


The PV tracker is a mechanical device which allows PV modules to receive the maximum direct sunlight throughout the day. Compared with a fixed tilt system, the PV tracker receives 10% ~ 30% more direct sunlight (Table 1), significantly improving the power output and subsequently reducing LCOE.

2. The principle of solar tracking system

PV tracking systems can be divided into three kinds: a horizontal single-axis tracker, a tilted single-axis tracker and a dual-axis tracker (Figure 3). The single-axis tracker has only one rotational degree of freedom, while the dual-axis tracker has two rotational degrees of freedom. According to real-world field data, a horizontal single-axis tracker can generate up to 10% ~ 20% more power, a tilted single-axis tracker up to 15% ~ 25% more, and a dual-axis tracker up to 30% more. The horizontal single-axis tracker showed a relatively lower reliability risk, while the tilt single-axis tracker and the dual-axis trackers showed a higher risk.

Many factors such as geographical conditions, local irradiance, and the purpose of the project need to be considered when designing a PV tracking system (Figure 4).
4. Reliability analysis of PV tracking system

Due to the market competing on price rather than on quality and reliability, numerous sub-standard products have been introduced and created a doubt over viability of PV plants over its assumed service lifetime of 25 years. Sicheng Wang, a Chinese PV system expert, pointed out that the most effective way to reduce LCOE is to employ a PV tracking system and resolve the reliability problem that hinders extensive adoption of the technology. In order to guarantee the maximum power generation over the lifetime of PV plants, developers would be required to select an optimal technology for the purpose of the project, implement quality control measures in each phase of the project development, and reduce cost by integrating a smart system and component design, not by sourcing the cheapest components.

A PV tracking system consists of four key components — support rails, bearings, motors & gear reducer, and controller. Three common failure modes are detailed below.

1) Motor failure: An environment with high humidity and high temperature can accelerate the aging of insulation and the formation of leakage current. Sand and moisture can penetrate into the bearings and damage them, and overheat the motor.

2) Control system failure: the timing controlling system was employed in the track-er.

3) Structure failure: Sinking land and slope cause rails to deform over time which would eventually prevent the axis from rotating. The core component of the rotating mechanism, the bearing, could fail. Inappropriate foundation design and poor construction cause the system to fail.

Components of the tracker should be tested in accordance with IEC 61701-2011 and UL3703 standards to ensure the reliability and durability. Test items should include mechanical loading test, salt fog test, dustproof and waterproof test, grounding continuity test, and a series of environmental aging tests such as thermal cycling, damp and hot, and UV resistance (Table 2).

5. Summary and perspectives

For a PV market which favors cost-effective smart PV systems, a PV tracker system should be considered. The recent trends for the PV tracker systems are 1) adoption of high-efficiency bifacial solar cells to increase the power generation and to reduce LCOE; 2) adoption of best MPPT tracker with smart controller chips to realize a maximum power generation; 3) adoption of the cloud platform to smartly manage the PV power plants.

Table 2 Reliability tests for key components of a PV tracking system

<table>
<thead>
<tr>
<th>No.</th>
<th>Parts name</th>
<th>Test Item</th>
<th>Reference standard</th>
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<tbody>
<tr>
<td>1</td>
<td>Rail fasteners</td>
<td>Anti-corrosion ability of rails &amp; fasteners</td>
<td>1. GB/T 10125-2012 corrosion test, salt fog test</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>2. IEC 61701-2011 PV modules salt spray corrosion test</td>
</tr>
<tr>
<td>2</td>
<td>Motor reducers</td>
<td>Environmental aging test, Protection grade test, Metal surface corrosion resistant test</td>
<td>1. GB/T 12065-2008</td>
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<td></td>
<td></td>
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<td>2. GB/T 12065-2008</td>
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<td>3. GB/T 3131-2010</td>
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<td>4. GB 200-2008</td>
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<td>5. L.S. 306.16</td>
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<tr>
<td>3</td>
<td>Control box</td>
<td>Environmental aging test, Protection grade test, Metal surface corrosion resistant test</td>
<td>1. GB 4208-2008 (IP)</td>
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<td></td>
<td></td>
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<td>2. GB 4208-2008 (IP)</td>
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<td>3. GB/T 12665-2008</td>
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<td>4. GB/T 2421.2-2001</td>
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Correlation of modules’ long-term reliability with indoor accelerated aging tests

Sangzhong Zhu, Hui Shen, Zhichao Ji, Jing Mao, Quan Sun and Jianmei Xu

Durability of modules in the field is attracting a growing attention in the PV industry. IEC standards are more effective for evaluating reliability of PV modules than long-term durability. The degradation mechanism of modules in the field should be investigated thoroughly, especially for harsh climates. Factors that influence module power degradation in an actual operating condition are different from those observed in an indoor accelerated aging test laboratory. This paper investigates the power degradation mechanisms in hot-humid and hot-dry regions with a series of accelerated aging tests in combination with ultraviolet irradiation.

1. Introduction

IEC 61215, the most authoritative standard in the PV industry, is not suitable to verify the durability of PV modules over warranted lifetime which has recently changed from 20 years to 25 years. Durability is the module’s ability to withstand the long-term degradation, affected by a combination of environmental factors, not just one.

Based on the Koppen climate classification, climates for PV module installations can be divided into four categories: hot-humid, hot-dry, temperate, and cold and alpine. Key environmental factors vary greatly from one climatic region to another. Key environmental factors are varied greatly from one climatic region to another [2]. N. C. Park et al. simulated the climate condition in terms of temperature and moisture using Eyring and Peck models. 10000hr damp heat (DH, 85 ℃, 85% R.H.) treatment was equivalent to an actual module operation of 23 years in a hot-humid region, 40 years in a hot-dry region, and 106 years in an alpine region [3]. The level of UV also varied for each region. W. Hermann et al. measured the daily temperature variation of modules in all four climate regions [4].

Figure 1 shows appearances of two five-year-old encapsulated modules with the same backsheet in temperate and hot-dry climates. Although both backsheets had been IEC 61215 certified by TUV Rheinland, it is clear that both backsheets degraded after five years of operation in field.

References

The thickness of Ag3Sn alloy could be estimated by diffusion dynamics equation below [5]:

\[ d = d_0 + \left( D_0 \exp \left( \frac{-E_a}{RT} \right) \right) t \]  

(Equation 1)

where, \( d \) is the final alloy thickness, \( d_0 \) is the initial thickness, \( D_0 \) is the diffusion constant, \( R \) is the gas constant, \( E_a \) is the reaction activation energy between Ag and Sn, \( T \) is the absolute temperature, and \( t \) is the dwell time at typical temperatures.

The power degradation mechanism of modules in the hot-humid region and the hot-dry region are different due to varying amounts of moisture, acid and sand. In the hot-humid region, the moisture ingress could accelerate the release of acetate acid as EVA decomposes and subsequently degrades the welding strength in the module. The main indoor accelerated aging test as EVA decomposes and subsequently degrades the welding strength in the module. The main indoor accelerated aging test

The cause of Rs increase in modules in Shenzhen was investigated by comparing metallographic cross-sectional images of modules in both places as shown in Figure 5. Cracks seemed to appear in Shenzhen modules’ welding spots. Cracks were caused by the weakening welding strength – to verify the thickness of Ag3Sn alloy in modules from both places were compared.

For modules in the hot-dry climate, Dunhuang, the short-circuit current (Isc) degradation due to the abrasion of the glass was the biggest contributing factor to the power degradation (Figure 4). Some FF degradation due to cell cracks was also noticeable. It is inferred that cell cracks were caused by the wind in Dunhuang.

The thickness difference may have been due to the formation of acetate acid from the degraded EVA and the moisture ingress which decreased the reaction energy. In order to demonstrate this, modules encapsulated with EVA of different VA content were fabricated, and the growth rate of alloy under highly accelerated stress test condition (HAST, 121℃+100% R.H.) was compared.

As the above equation states, the thickness of Ag3Sn is affected by the temperature, the time, and the reaction energy. Any thickness difference may have been due to the formation of acetate acid from the degraded EVA and the moisture ingress which decreased the reaction energy. In order to demonstrate this, modules encapsulated with EVA of different VA content were compared, and the growth rate of alloy under highly accelerated stress test condition (HAST, 121℃+100% R.H.) was compared.

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of sequential qualification tests combined with UV and DH test. The acetate acid could accelerate the weakening of welding strength by increasing the growth rate of Ag3Sn alloy. The indoor accelerated aging test which could simulate the module degradation in the hot-humid region is the damp heat test. However the absence of UV light in the test results in underestimating the amount of acid formation. Thus, the damp heat test combined with UV light would be an appropriate method to evaluate the durability of modules. The thermal stress related failure could be simulated by the thermal cycle test, however, the temperature ramp rate on different types of modules could not be evaluated in this test. Introducing the thermal shock test could assist in assessing the durability variance among different types of modules.

Reliability of silicone structural adhesive in PV module

Jing Mao, Hao Lu, Qiangzhong Zhu, Hui Shen, Yue Zong, Zhichao Ji

A full set of environmental tests in IEC61215 was carried out to analyze the bonding reliability of the silicone structural adhesive in installed solar modules. Additional non-standard tests were also carried out in simulated outdoor condition. The analysis verifies that the silicone adhesive can ensure the safety and the reliability of PV modules over long term.

1. Background

With increasing demand of PV generation, customers expect higher quality and highly reliable PV products. Dual-glass modules are designed for high reliability in harsh regions, in particular, tropical, arid, marine and corrosive environments -glass modules are designed for high reliability in harsh regions, in particular, tropical, arid, marine and corrosive environments. The hook is compatible with commonly fast installation, and can withstand the wind load capacity of a dual-glass module. The hook is made of aluminum alloy, has a “cross-hole” design, which ensures an accurate and fast installation, and can withstand the wind load capacity of a dual-glass module. The hook is compatible with commonly available brackets on the market.

2. Environmental Reliability Test

2.1 Type selection of silicone adhesive

According to ETAG002 e [2], silicone bonded samples were kept in a water bath at 45°C for 21 days. This test condition was chosen to determine the properties of the silicon adhesive. During the development stage of dual-glass modules with the rear rail hook attached, stringency of the reliability test was increased and the water temperature was raised to 55°C. The pass criterion was set at 85% adhesion level or Cohesive Failure (CF) after 21 days in the hot water bath. We selected two kinds of adhesives from manufacturer A and manufacturer B. The adhesive from manufacturer A lost adhesion to the glass after first 7 days as shown in Figure 1a, while the adhesive from manufacturer B met the requirements and passed the hot water bath test (55°C, 21 days) retaining 85% of CF area as shown in Figure 1b. The silicon adhesive of manufacturer B was selected for evaluation in the following reliability test.

2.2 Conventional Environmental Test

Test samples were prepared to evaluate the mechanical properties of silicone structural adhesive in PV module. According to ETAG002 e [2], silicone bonded samples were

References


Figure 1

(a) Adhesive from manufacturer A showed failure after HAST test; (b) Adhesive from manufacturer B passed HAST test

Figure 2

(a) Pull and shear forces applied during the environmental test; (b) Degradation of the pull and shear strength post environmental tests
strength in two perpendicular directions (pull strength and shear strength) to assess the force bearable by the rail attachment hook as shown in Figure 2 (a). In the standard test, the adhesive showed the largest mechanical degradation post DH test (Figure 2 (b)). The following analysis focused on evaluating the bonding performance under high-temperature and high-humidity environment.

Adhesive is sensitive to the moisture and showed high water vapor permeability in humid test conditions and tended to hydrolysis, in particular, in high-temperature and high-humidity environment causing the bond strength between the filling and the attached bonds to degrade.

The reason for this degradation is sensitivity of silicone to water vapor and its high water permeability. It is prone to hydrolysis, which leads to lower mechanical strength of the polymer chain.

DH test verifies the long-term moisture penetration ability of the material. Following the standard test procedure, the most degradation in mechanical performance is evident post DH test. The duration of DH test was extended to 3,000 hours to more realistically simulate the real-world environment the module is installed in. To assess the reliability of silicone structural adhesive, the mechanical degradation was recorded and is shown in Figure 3. The adhesive could still maintain more than 80% of its mechanical strength after DH3,000 test. It is inferred that due to the main polymer chain of the silicone structural adhesive being composed of Si-O bonds, which are not affected by the high-temperature and high-humidity environment causing the bond strength between the filling and the attached bonds to degrade.

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2.3 Bonding strength of the adhesive in acidic and alkaline environment

The adhesive’s bonding strength with the glass surface was tested after 7 days of pH1 and pH13 immersions. 1 Glass samples with silicone adhesive were left in acidic and alkaline solutions for 7 days (Figure 4) and at the end of 7 days, a peeling test was performed on each sample. The acidic solution was composed of 5% H2SO4 in water (pH=1) and the alkaline solution was composed of 5% NaOH in water (pH=13). The area of cohesive failure was 85% after the immersion in either the acidic or the alkaline solution.

3. Mechanical loading test of a dual glass module with hook attachments

A full set of environmental tests in IEC61215 was carried out on a dual glass module with hook attachments on the rear to explore and analyze the strength and reliability of the adhesive bonding. A number of non-standard tests with several times higher stringency than required by IEC61215, were also developed independently at SKL PVST to further evaluate the reliability of silicone structural adhesive (Table 1).

4. Conclusion

The lifetime of currently used silicon adhesive is relatively shorter than that of metal and glass parts in a PV module. To prevent potential premature failure of PV modules installed in field, it is necessary to ensure the adhesive used in PV modules can survive the harsh environments the modules often get installed in.

Representative climatic conditions should be selected to assess the hook attachment with silicone structural adhesive. Our work focuses on the analysis of the water permeability of silicone structural adhesive and the oxidation of hook material. Silicone structural adhesive which has more than 40 years of history in the field of building and is known to have a 20-year lifespan on the facade glass could fulfill the demand for the high reliability in the PV industry.

A small number of samples were made to perform non-standard simulation experiments. The hook attachment were hung in the real-world environment with continuous loading (6h and negative 3000Pa) applied at equidistance intervals (Figure 5) to simulate wind and snow loading on modules installed in the field. Test sites in Changzhou, Guangzhou, and Xinjiang, each region representing a typical climatic condition, were selected to carry out the experiment. Figure 6 shows that test samples showed no bonding failure after a year of exposure.

References


Table 1: Non-standard tests (aging and mechanical loading) of dual glass module with hook attachments

<table>
<thead>
<tr>
<th>Indoor accelerated test</th>
<th>Mechanical loading after aging</th>
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<tr>
<td>DH3000</td>
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<tr>
<td>TS500</td>
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<tr>
<td>TC500</td>
<td>Pass</td>
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Figure 3
Degradation in the strength of “pull” and “shear” after an extended DH test

Figure 4
The anti-acid and alkali performance of adhesive

Figure 5
6h/3000Pa mechanical loading test of a module with silicone adhesive

Figure 6
Concrete block hanging test [left: Xinjiang, Middle: Changzhou, Right: Guangzhou]

Reliability of polyolefin encapsulant in a PV module
Zhichao Ji, Hui Shen, Qiangzhong Zhu, Jing Mao, Quan Sun, Jianmei Xu

Polyolefin (POE) is an ideal choice as an encapsulant to replace Ethylene-Vinyl Acetate (EVA). POE is anti-PID (Potential Induced Degradation), has a lower water vapor transmission rate (WVTR) and does not release acetic acid. Harsh long-term accelerated aging tests were conducted on both encapsulant materials and modules to investigate the reliability. POE was found to have more reliable and better anti-PID properties.

1. Background

With the continuous development of society, energy shortage, environmental pollution, had become the biggest challenges. And they had been put into the agenda of the national development. It resulted in the rapid development of photovoltaic (PV) modules which could transform clean, renewable solar energy into electricity. The PV modules usually had 25 years’ service life. Thus the encapsulant materials played an important role in sealing and protection of the solar cells. However, discoloration and cracks were detected in the encapsulants, which could withstand the multistage of high temperature, oxygen and UV [1]. Otherwise, delamination and corrosion would occur with the action of moisture and heat [2]. They would greatly reduce the service life of the PV modules. Therefore, the development of the highly weatherable encapsulant film became the key to improve the life of photovoltaic modules.

Polyolefin (POE) had attracted extensive attention in recent years due to its superior performance like free of acetate groups and without the acetate release and corrosion as compared with EVA in the actual operational environments. Moreover, the moisture ingress rate is only 1/6 of that of EVA, and thus dramatically reduces the risk of water vapor permeability, which showed great application potential in the hot and humid climatic regions. Another advantage lies in the excellent anti-PID performance with the POE encapsulated solar modules, especially in the high-efficiency solar modules.

2. Anti-PID research of POE

PID problem is worthy of gaining much attention as a common technical problem with the development of photovoltaics. The PID test is conducted under 85°C and 85% R.H. with the front and rear of the module wrapped by Cu foil, by applying negative bias of 1000V voltage for 102h. Figure 1A compared the electrical performance of the EVA and POE encapsulated modules that was connected by anti-PID solar cells and solar cells free of anti-PID. Figure 1B showed the EL images of EVA and POE encapsulated modules before and after PID test. By comparison, the current EVA adopts anti-PID ingredients. Nowadays the interest of PID problem was growing up, because it could dramatically reduce the yield of the PV power plan. Power and energy reductions higher than 30% had been determined which leads to an important decrease in the economic performance of a PV installation. In this paper, PID experiments, modules covered with copper foil in both sides at 85℃ and 85%RH, with the negative bias 1000V, were conducted. Figure 1A and 1B showed the electric properties and EL pictures of EVA and POE encapsulated PV modules after PID experiments with 102h. Due to the anti-PID ingredients used in the current EVA, there shows no obvious advantages in POE. The power degradation were both less than 0.5%. However, when PID-free cells were used, the power degradation of EVA encapsulated modules reached up to 14.4%. While in POE modules were only 1.6%, which was a significant advantage compared with EVA the POE is free of acetic acid, AND showed lower polarization under high temperature and applied electric field. Besides, POE had smaller WVTR than EVA, which would also improve the anti-PID properties.

3. Researches on POE reliability

POE encapsulated solar modules showed better reliability in the operational regions characteristic of high temperature and high humidity. In order to investigate the corrosion mechanism of acetic acid in EVA, HAST (Highly Accelerated Stress Test) experiments of EVA and POE modules were conducted under 121°C and 100%RH. The electrical properties and EL images were compared here. The power degradation of EVA encapsulated conventional module was mainly resulted from the reduction of the fill factor (FF) which was caused by the decreased series resistance. It could be contributed to the larger water vapor ingress and thus the bus bar corrosion caused by the released acetic acid in high temperature and humidity could be clearly observed in EVA traditional module, which could hardly be observed in POE traditional module and the EVA dual glass module. It implied that the water vapor ingress and the acetic acid would accelerate the growth of the Ag3Sn.

Figure 1A (The electrical properties of EVA and POE encapsulated PV modules with different cells before and after PID test); B) The EL images of PID-free cells before and after PID test, a) EVA module, b) POE module.

Figure 2 presented the power, FF and EL degradation of EVA and POE encapsulated traditional and dual glass modules after HAST test of 480h. (121°C, 100%R.H.). Compared with Figure 2c and 2e, the bus bar corrosion caused by the released acetic acid in high temperature and humidity could be clearly observed in EVA traditional module, which could hardly be observed in POE traditional module and the EVA dual glass module. It implied that the water vapor ingress and the acetic acid would accelerate the growth of the Ag3Sn.

Figure 2 (a),(b) The power and FF degradation of EVA and POE encapsulated traditional and dual glass modules after HAST test of 480h; (c),(d) The EL images of EVA and POE encapsulated traditional and dual glass modules after HAST test of 480h.

The acetate released from the EVA would accelerate the growth of the Ag3Sn. This would result in the decrease of the welding strength, making it easier to fail at the welding point due to the thermal fatigue damage. In Figure 3a the Ag in EVA encapsulated module was reacted with Pb to transform into Ag5Sn after HAST test. The thickness of Ag5Sn was about 13μm. While in POE encapsulated module, the interface of Ag and Pb was still obvious. And the thickness of Ag5Sn was only 5μm.
The current installation of the terrestrial photovoltaic power plants accounts for more than 80%, of those, PV plants in the arid area accounts for approximately 60% where PV module surface dust and the abrasion on the glass coating have a strong influence on the output power. The purpose of this study was to develop a “Sahara module” suitable for the arid desert environment, and to verify the reliability of the module and its feasibility in other harsh climatic conditions. The results show that compared with conventional modules, the Sahara module has clear advantages due to its anti-abrasive surface glass coating, wind-resistant performance and self-cleaning property.

Development of Sahara module with high wearability
Yeyi Jin, Shu Zhang, Jianmei Xu

The current installation of the terrestrial photovoltaic power plants accounts for more than 80%, of those, PV plants in the arid area accounts for approximately 60% where PV module surface dust and the abrasion on the glass coating have a strong influence on the output power. The purpose of this study was to develop a “Sahara module” suitable for the arid desert environment, and to verify the reliability of the module and its feasibility in other harsh climatic conditions. The results show that compared with conventional modules, the Sahara module has clear advantages due to its anti-abrasive surface glass coating, wind-resistant performance and self-cleaning property.

1. Background

In arid desert areas, dust accumulated on the surface of a photovoltaic module is the main cause of power output reduction. Studies have shown that up to 80% of the PV module power generation can be reduced due to surface dust accumulation [1]. The glass coating of the current PV modules gets damaged after a long-term exposure to sand abrasion in the harsh desert region, resulting in large power output degradation [2]. Therefore some PV power plant developers prefer to use uncoated glass modules and sacrifice the generation boost in the beginning that would have been possible with the coated glass modules, rather than observe large power decay as the plant ages. SKL has developed “Sahara Module” with a highly abrasion-resistant AR coating and a dual glass structure.

2. Processing optimization of Sahara module

Sahara module is built with the same structure as the conventional dual glass module. The module optimization was carried out with climatic features in the desert region in mind, as illustrated in Figure 2.

The hardness of conventional AR coating on a PV glass is only 4H. Its porous structure is highly susceptible to erode by sandstorms. A dense AR coating with the hardness of ≥6H was used for Sahara module. It could effectively withstand the abrasion from sands and ensures a long-term stable output of the module. Therefore some PV power plant developers prefer to use uncoated glass modules and sacrifice the generation boost in the beginning that would have been possible with the coated glass modules, rather than observe large power decay as the plant ages. SKL has developed “Sahara Module” with a highly abrasion-resistant AR coating and a dual glass structure.

References
### Advantages of Sahara module

#### 3.1 High wearability

The wear test standard (EN1096-2) [3] was used to characterize the wearability of the coating with 450g load on the coating surface as shown in Figure 5. Post 500-cycle friction test, the conventional AR coating with a hardness of 4H has completely eroded and the erosion led to a transmittance gain of 2%. The dense AR coating with a hardness of more than 6H maintained a good film structure after the 5000-cycle friction test.

#### 3.2 Sand blowing test

The test criteria of sand blowing test in GB/T150.12A-2009[4] (military applications) were employed - wind speed of 20m/s, sand density of 2.5g/m³, inclination of 45 degrees and two test durations of 90min and 120min. The dust accumulation on the module glass surface is approximately 7.5g per year for a single module in Toksun, Xinjiang, China. The 90min indoor sand blowing test is equivalent to the sand blowing for more than 15 years. Figure 7 compares the transmittance of the dense AR coated glass and the conventional AR coated glass during the sand blowing test - the wearability of dense AR coated glass is significantly superior.

#### 3.3 Weatherability of Sahara module

Accelerated aging test of the conventional AR coating and the dense AR coating was conducted in accordance to the environmental test conditions set in IEC61215 and UL1703. Each test was repeated several times and the result is shown in Figure 8. Post harsh DH and HF tests, serious corrosion and "rainbow" spots were observed on the surface of the conventional AR coating, while the surface of the dense AR coating remained relatively undamaged post HAST, DH, HF and UV+DH tests. It is inferred that the porous surface structure of the conventional AR coating, composed of spherical SiO₂ nanoparticles with gaps in between, allows penetration of surrounding water vapor and salt molecules into the coating and the glass substrate. This causes the coating to corrode from the inside out and to eventually erode. In the dense AR coating, SiO₂ molecules wrap around organic molecules which get removed by high-temperature sintering; the remaining molecules are bonded closely together by Si-O bonds and the tight bonding prevents water vapor and salt molecules from entering into the coating and the glass substrate, ensuring good weatherability of the module.

#### 3.4 Self-cleaning ability of Sahara module

Compared with a conventional AR coating and a tempered glass, the surface of a dense AR coating in a Sahara module has a higher surface tension due to a presence of charged Si-O bonds and variations in nanoparticle sizes, which creates a tiny electrostatic field that prevents fine dust particles from adhering onto the surface. Such characteristics of the dense AR coating lead to excellent "self-cleaning" performance. Combined with the inclination angle of an installed module and the external force such as wind, it is difficult for dusts to accumulate on the module surface. Such self-cleaning ability of a module enhances the power generation and reduces the maintenance cost of power plants. To demonstrate highly packed surface of the dense AR coating, carbon powder was sprayed onto the surface of both types of glasses, and dusted off by erecting the glass up. The carbon powder left no residue on the dense AR coated glass, whereas the conventional AR coated glass had some residual power left on it (Figure 9).

#### 3.5 Enhanced power output of Sahara module

A group of modules, some with dense AR coating and some with conventional AR coating, was installed at a testing site in Toksun, Xinjiang, China to investigate the real-world performance of Sahara modules. Figure 10 illustrates the performance of dense AR coated modules and conventional AR coated modules in kWh/kWp measured over a period of seven months. The dense AR coated modules demonstrate superior performance compared with conventional AR coated modules - the generation gain for the dense AR coated modules was 14%el.

### Summary

The Sahara module, with a combination of the double glass structure and a highly dense AR coating on the front glass, is highly resistant to moisture ingress, corrosion and sand/dust accumulation. Its power output is not only higher than the standard module but also stable over a long-term period even when installed in a harsh environment. Sahara modules can be installed not only in an arid desert environment, but is also suitable for coastal regions. The transmittance of the AR coating and the self-cleaning ability of Sahara module can be further optimized to improve the power output and to ensure the long-term reliability of the module.
2. R&D of system components

2.1 Trinapeak smart module

SKL launched a cell-string optimizing module, Trinapeak, which can perform maximum power point tracking (MPPT) on a cell-string level. The Trinapeak module contains 3 MPPT optimizers instead of 3 bypass diodes as in a conventional module. The optimizer can boost up the current of the weakest cell-string to match that of the other two series-connected strings. The optimizer can also be compatible with inverter. Both the optimizer and the inverter work at different levels of MPPT and ensure the optimum output of the system at different environmental conditions. Trinapeak has many merits compared to a conventional module.

1) Enhancement of system energy yields: In a conventional module, three bypass diodes work as a protection mechanism. They enable the module to generate power even when a cell-string is partially shaded or damaged. When the bypass diode triggers, the string of cells in parallel to the bypass diode does not contribute to the module power output. However in Trinapeak module, the module loses only a part of power in proportion to the shading. Depending on the shading condition, Trinapeak can have 3%~20% higher energy yield than a conventional module.

2) Elimination of hot-spot effects: when the operating current of a module is higher than the short circuit current of a shaded or defective cell-string, the module has a hot spot effect. The cell operates under reverse-biased voltage and dissipates power through heat, the cell overheats. The cell-string optimizer in Trinapeak can automatically adjust the current and voltage of the shaded cell-string to match those of the others, and the shaded cell continues to operate under the forward-biased voltage. Thus, the Trinapeak module doesn’t have hot spot effect (see Figure 1 below).

1. Background

Trina inverter is aimed at the residential market. Its rated capacity ranges from 3kW to 60kW. Trina inverter has many different types including a single-phase with a single MPPT input, a single-phase with dual MPPT inputs, a three-phase with low capacity and a three-phase with medium capacity. It complies with the regulation required for residential and commercial rooftop projects. Sunbox is a turn-key solution for residential PV systems which provides all system components including PV modules and BOS, and installation and grid connection services. In recent years, the State Key Laboratory (SKL) has been working on distributed system applications and system component optimization.

2. R&D of system components

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References

2.2 Trina Solar Inverter

Trina Solar inverter has a power range of 3kW-60kW, and includes three main models: a single phase with a single MPPT, a three-phase with dual MPPT, a three-phase with four MPPT. (For specific parameters see Table 1).

Trina solar inverters are all transformerless which can achieve a higher efficiency than a conventional inverter with a transformer and takes up less space. Trina inverter also has a wider start-up voltage and MPPT voltage ranges. For example, the start-up voltage of a 3kW inverter is as low as 80V - it means that the inverter can get more energy production at low irradiation condition. The inverter between 3kW and 25kW power range has dual MPPT inputs and between 50kW to 60kW power range has 4 MPPT inputs. Multi MPPT feature can accommodate multi-angle and multi-orientation systems, and allow for more flexible system design options. Trina inverter has more than 20 protection functions from arc, overvoltage/undervoltage, overfrequency/underfrequency, over current, over temperature, reverse polarity, and leakage current. Each function may alert the user in real-time by an error code. All inverter’s maximum efficiency is over 98.5%. The maximum efficiency of 60kW inverter is over 98.8%. All inverters meet IP65 and are suitable for outdoor wall-mounted use. Trina inverter optimizes the software algorithms, topology and components.

Table 2: Reliability tests for key components of a PV tracking system

From Figure 2 we know that Trina inverter has a wider range of maximum power point voltage than a conventional inverter. The efficiency stays high and uniform across the entire operating voltage range. At low power, the efficiency is above 92%. At full power, the efficiency is above 96%. When the operating voltage is around 380V, the efficiency can reach up to 97.8%.

Figure 2

The MPPT efficiency demonstrates the inverter’s ability to track the maximum power point of a PV array. The MPPT efficiency includes static and dynamic efficiency. The MPPT efficiency is tested by comparing the instantaneous voltage & current sampled from the inverter input and the maximum power point of a preset I-V curve in a PV Simulator.

Static MPPT efficiency reflects the MPPT accuracy of an inverter in a given static I-V curve of PV module. Figure 3 is the static MPPT test results of a 10kW Trina inverter.

Figure 3

When an inverter’s working curve changes, MPPT efficiency varies and the inverter has power loss. Trina inverter uses new software algorithms with dynamic MPPT time of 3s, which is much lower than the standard value of 10s. As the outdoor irradiance constantly varies, the faster MPPT response time means the higher energy production.

2.3 PV module mountings

PV system mounting is an important system component to ensure stable and safe operation of a PV project during its lifetime. PVST SKL designed a wide range of mountings for various installation scenarios.

1) Roof tile mounting (’tile’ includes ceramic tiles, slate tiles, and asphalt shingles etc.)

The roof tile mounting is usually employed in residential systems in Europe, America, Australia, other developed countries, and China. Residential systems usually have a small installation capacity, mostly ranging from 2kW to 10kW. A roof tile mounting design needs to take into account of the structural integrity of the house (tile shape, material, span and slope of support beam, etc.) and the local meteorological condition such as wind, snow and rainfall etc.

2) Color steel roof tile mounting (trapezoidal tile, and standing seam tile)

Color steel roof tile mounting is usually used at industrial sites. Different color steel tile has different installation supports and fixtures. Clamping method is preferred with this mounting since it is easy to install, and doesn’t damage the roof.

3) Flat roof mounting

Flat, concrete roof mounting is mainly used at industrial sites. This structure is usually installed by placing concrete blocks or a ballast onto the loading tray of the mounting.

4) Ground-mounting

Ground-mounting is usually used in a large scale PV proj-
2.4 Residential system components

Sunbox is a turn-key solution for residential PV systems which provides all system components including PV modules and BOS, and installation and grid connection services. It can be installed on various types of residential roofs. Sunbox is one-stop service solution which includes purchasing, installation, and maintenance. It is a standardized product with efficient procurement cycles and fast delivery.

Sunbox contains PV modules, an inverter, a grid-connect cabinet, a mounting, cables and other distributed PV system components. Users have options to customize and upgrade the system. Trina SKL controls the quality of all system components and designs to optimize the energy production and the reliability of the system.

3. Conclusions

Distributed PV market in China is expected to go through a significant growth in the coming days as the national policies are being drafted to foster the distributed PV market. In the “Thirteen-Five” period, PV poverty alleviation projects will reach 15GW in total - distributed PV systems will account for about 5GW. In recent years, Trina SKL launched the Trinapeak smart module, a residential inverter, the Sunbox system solution, mountings, and other distributed PV system components. Trina will continue to focus on research and development of high efficiency and high reliability system products and smart PV modules.

References


Evaluation of energy performance & reliability of PV systems with various types of PV modules in typical climates

Dengfu Xia, Peng Quan, Ying Zhang, Zhichao Wang, Jiaxiang Qian

The outdoor empirical test platform of photovoltaic system under the typical climates is constructed based on the problems of photovoltaic modules in the actual operating environments. The testing methods and the results are presented in detail. Experimental results and analysis clearly indicate that the designed test platform can predict the performance in the actual operating environments with good accuracy.

1. Introduction

Photovoltaic products are subjected to varying environmental conditions such as light intensity, humidity, temperature, and heat. They are also subjected to other factors specific to each application. The permutation of these factors are difficult to accurately simulate in an indoor laboratory environment and need to be studied through empirical analysis of outdoor PV systems. First half of this paper describes how the outdoor testing platforms were set up and which testing methodology was employed. The second half of this paper analyses the energy output and reliability of outdoor PV systems with various types of PV

2. Experimental

2.1 Outdoor empirical testing sites

The module testing sites were set up in various climatic conditions. PV modules made of different materials and technologies were installed and there were also variations at system component level. Conventionally in laboratory testing, the power output test and the accelerated aging test are carried out separately. However, in the real-world, PV module outputs are measured whilst the modules are gradually degrading. To more accurately observe and analyze this real-world impact, the power output test and the accelerated aging test were combined for our testing. Pictures of new module testing sites both planned and constructed by Trina Solar - are shown in Figure 1. Meteorological characteristics at Changzhou, Turpan, and Yunnan are presented in Table 1. The energy performance and module reliability tests have been designed to account for extreme environmental conditions such as high UV, high temperature and high humidity as well as urban pollution and acidity.

3. Results and Discussion

3.1 Outdoor Energy Yield/PR testing

The energy yield of photovoltaic modules is affected by ambient temperature, irradiation, spectrum and the angle of incident light. The module component materials (eg. cells, glass, EVA, back sheet) and the manufacturing processes also affect the module output. For example, the glass coating material and the coating process could change the transmittance and the self-cleaning ability of the glass, and subsequently have an influence on the module’s power output, a glass surface with specific light trapping technology or a sol-
der strip with inbuilt reflective microstructure could increase the amount of light that is absorbed by cells and subsequently increase the energy yield of a module.

A long-term outdoor energy yield testing was performed on five types of modules. All the modules were made up of the same materials and processes but had different types of glass – some modules had ARC, while some did not have ARC. Pre-conditioning and the subsequent power measurements were conducted in an indoor laboratory on two to three sample modules which were taken from each module type. Based on the data from Trina Solar Changzhou outdoor testing site taken from 6th June, 2015 to 28th July, 2015, (shown in Figure 2) all modules with ARC performed better than modules without ARC. The maximum yield was approximately 2%.

Figure 3(2) shows the energy yield of the sample modules with different manufacturing processes at Trina Solar Changzhou outdoor testing site between 16th July, 2014 and 1st September, 2014. The outdoor sample module output is similar to that of indoor power output under low irradiation which is similar to the irradiation condition in Changzhou. It can be inferred that, for low irradiation condition, indoor laboratory testing can be a good estimate for modules’ real-world performance. This is good because, in the case of high performance modules, the module performance under low irradiation also matters, in addition to the module performance at STC.

Figure 3(1) shows the energy performance of modules in an outdoor testing site.

3.2 Measurement of Incidence Angle Modifier (IAM)

IAM measurements were carried out to analyze the effects of different incident angles on the performance of PV modules. Figure 4 shows the adjusted IAM result of four modules which were tested at Trina Solar Changzhou outdoor testing site. The IAM value is greatly affected by outdoor weather conditions and errors in the results were large. Therefore, multiple modules should be selected and tested at the same time under ideal conditions (high irradiation, high direct irradiation ratio, no wind, stable weather).

3.3 Reliability testing of module component materials and modules

The long-term reliability tests included “hot-spot” test, PID test and LID test. The hot-spot testing result infers that a smart module is able to dissipate the heat better than a conventional module (Figure 5). When a hot-spot incurs in a PV system, the current in the shaded cell does not clip the entire string current as the current in the shaded smart module is increased to match the current in the string. This prevents the bypass diode in the string being activated and the series cell voltage continues to contribute to the overall module power output, effectively eliminating the hot-spot phenomenon.
4. Conclusion

The results and the analysis indicate that the outdoor practical verification test is definitely worthy of promotion. Based on the testing experiences, the following proposals are made for outdoor tests:

(1) Conduction of outdoor energy yield tests to test real power generation capacity of the module.
(2) Reliability testing of materials and modules (outdoor hot spot, PID, decay, aging) to research aging.
(3) Testing of low irradiance performance and power performance at high temperature.
(4) Due to the lack of standard references for testing, accuracy needs to be improved and the research will continue to do so.

References


LCOE modeling and analysis of the main influence factors

Kai Sun, Peng Quan, Bangtang Ding, Shengcheng Zhang, Ashray Udayashankar, Kang Jian, Zhen Zhang

A LCOE calculation model was developed according to the definition of LCOE and present situation of China. Evaluation of average LCOE level for photovoltaic (PV) projects and analysis of main influence factors of LCOE were made through the model. Meanwhile, the variation trend of LCOE in China was predicted.

1. Background

LCOE is an abbreviation for the Levelized Cost Of Electricity, a term coined by Fraunhofer-ISE, Germany. LCOE represents the cost per unit energy production during the lifetime of a PV system and could be calculated using the following formula:

$$\text{LCOE} = \frac{C_t}{E_t} \times \frac{1 + d}{1 + d^N}$$

Where $C_t$ is the cost of the project in year $t$, and $E_t$ is the energy produced by the PV system in year $t$, and $d$ is the discount rate, and $N$ is the lifetime of the system. Since the lifetime of a PV project is usually 25 years, the time value of money needs to be taken into account when calculating LCOE, and both cost and energy production are discounted [1, 2].

The continued improvement of PV technology and manufacturing, and the reduction of construction cost of PV projects have resulted in LCOE reduction. The PV industry has strived to realize the grid parity during the period of 13th Five-Year Plan. Notably, the low price bidding in PV projects and adjustment of feed-in tariff policy released by National Development and Reform Commission caught the attention of PV practitioners.

What is the average LCOE in PV industry? How to rationally build LCOE model and evaluate it? What is the significance of LCOE analysis? In order to answer these questions, we put forward a LCOE model with a focus on the domestic market in China, evaluate the current LCOE and the main influence factors, and predict future scenarios of the LCOE trend.

2. LCOE Modeling

LCOE is a simplified way of showing cost per unit energy, expressed in $/kWh. The system cost takes into account of initial construction cost, maintenance and operation cost during the system’s lifetime, and the residual value at the end of lifetime. The energy production is affected by the system performance, location, and installation method. LCOE does not take into account of financing relates matters, discount rate, state and/or federal policy, and these need to be carefully considered for detailed analysis of true energy cost. The core concept of LCOE modeling is to build up a rational frame work, taking a top-down approach – i.e. each component is broken down into smaller and more detailed constituents. For example, the initial construction cost is divided into four parts – the basic equipment cost, the installation and construction cost, the project management cost, and finally the land lease cost. The basic equipment cost is further divided into modules, mounts and inverters and so on.

Boundary conditions need to be established for LCOE since it is affected by numerous factors including the solar energy source, system performance ratio (PR), the loan and discount rates. The boundary conditions for all analyses in this study are set as follows.

- System capacity: 10 MW
- Module price: 3.0 Yuan/W
- PR: 80%
- Ratio of inverter capacity to system capacity: 1.1
- Discount rate: 7%
- Loan rate: 4.9%
- Loan term: 15 years
- Loan to value ratio: 70%

The current LCOE for three kinds of solar energy resource regions in China are 0.545, 0.681 and 0.818 Yuan/kWh, respectively (Table 1). The cost distribution of initial construction and basic equipment is shown in Figure 1.

![LCOE modeling and analysis of the main influence factors](image-url)

**Table 1. Characteristics of typical climates**

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3. Analysis of Main Influencing Factors

Various factors affect the LCOE of a PV project. In this section, four main factors are discussed.

3.1 System Construction Cost

The impact system construction cost has on LCOE is analyzed while the total energy production remains constant. The current construction cost of a PV project is less than 7 Yuan/W. Since the module cost is the largest component of the initial construction cost, approximately 49% to be exact (54.7% x 37.0% = 20%), the module price has been selected as a representative construction cost. The test criteria are the same as the above-mentioned with the “second class” 1200 peak-hour solar irradiation. Result of impact an increasing module cost has on LCOE is shown in Figure 2 - when the module price is reduced by 0.1 Yuan/W, LCOE is reduced by 0.01 Yuan/kWh, which means the other cost variations in construction cost part have the similar effects on LCOE, such as mounts, inverters, installation.

3.2 Solar Irradiation and PR

Solar irradiation and system PR have significant impacts on LCOE. Three regions in China with different types of solar irradiance have been selected for this study. Each region has been classified according to the number of peak hours in a year - more than 1400 hours has been classified first class while less than 1200 hours has been classified the third class, between 1200 and 1400 peak-hour region has been classified the second class.

Figure 3 shows the correlation among LCOE, peak hours and PR. LCOE decreases with an increase of peak hours - as the peak-hours increase from 1000 to 1800 hours, LCOE is reduced by 44%. However, LCOE is inversely correlated to PR. For example, LCOE is reduced by 17% when PR is increased from 75% to 90%. Though the first class region has an advantage of high peak hours, we still have to objectively notice the existing phenomenon of limited energy production.

3.3 Discount Rate and Loan Rate

PV projects belong to commercial investment. Tax, loan and related capital financial are usually included in PV projects as a result of high cost and long operating period. Therefore, representative discount rate and loan rate were selected as an example to study the effects of financing on LCOE (Figure 4) with 1200 peak-hours. LCOE is increased by 4% as discount rate is increased by 1%. LCOE is increased by 3% as loan rate is increased by 1%. We have to fully evaluate the economic development situation on the investment side.

3.4 Innovative Technology Development

Despite the initial capital injection for new products and technologies development, the benefits of increased energy generation reduce LCOE. As the technology matures and the economies of scale reduce the cost, LCOE is further reduced. For example, introduction of smart modules and tracking systems have increased the cost, however LCOE was reduced because of significant increase in energy production (Figure 5). The ongoing operation and maintenance cost with smart modules is relatively the same, if not lower, compared to the conventional modules, while the energy production is significantly higher during the lifetime of the system; subsequently, LCOE is reduced. Not all currently available smart modules result in reduced LCOE if the additional energy production does not offset the increase in cost - for example, a bifacial module in Figure 5.

The analysis was carried out with the assumptions set above and the peak-hour of 1200 hours (second class).

4. Variation Trends of LCOE

As the PV component technologies and manufacturing technology advance, the cost of PV projects will decrease and the subsequent LCOE will also continue to fall during the period of 13th Five-Year Plan [3]. However, the scarcity of suitable land, increasing labor cost and limited room for equipment price drop are expected to resist significant reduction in LCOE in future. Table 2 presents future scenarios of LCOE for the coming four years.

Table 2 - Variation trends of LCOE during the period of 13th Five-Year Plan

<table>
<thead>
<tr>
<th>Year</th>
<th>Unit</th>
<th>First Class</th>
<th>Second Class</th>
<th>Third Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Yuan/W</td>
<td>0.545</td>
<td>0.641</td>
<td>0.818</td>
</tr>
<tr>
<td>2017</td>
<td>Yuan/W</td>
<td>0.538</td>
<td>0.647</td>
<td>0.777</td>
</tr>
<tr>
<td>2018</td>
<td>Yuan/W</td>
<td>0.492</td>
<td>0.615</td>
<td>0.738</td>
</tr>
<tr>
<td>2019</td>
<td>Yuan/W</td>
<td>0.467</td>
<td>0.584</td>
<td>0.701</td>
</tr>
<tr>
<td>2020</td>
<td>Yuan/W</td>
<td>0.444</td>
<td>0.555</td>
<td>0.666</td>
</tr>
</tbody>
</table>

5. Conclusion

We have successfully developed a LCOE calculation model according to the research of PV industry in China. The estimation of current LCOE level, analysis of main influence factors, and prediction of variation trends were made. It is feasible to realize grid parity in 2020 based on the current situation and development of PV industry.

References


*Percentage stated below the smart module type label on the x-axis represents the energy gain relative to the conventional module.
R&D of c-Si PV manufacturing equipment and its progress

Zhiqiang Ding, Chunyan Zhang, Zemin Yang, Liusheng Zhu, Haining Li, Lie Liu

PV equipment research center researches and develops new and existing manufacturing equipment domestically as the PV technology advances and the industry grows at an accelerated rate, requiring reliable and high throughput equipment. This paper focuses on the development of multi-functional laser doping equipment, an automatic contactless loading machine, an EL defect-detection vision system and a multi-bus-bar stringer.

1. Background

The rapid development of PV industry and the continuous advancement of processing technologies are requiring the PV manufacturing equipment to accommodate newly developed processes, higher throughput and optimized performance. The main purpose is to provide a favorable realization schema for the laboratory experiments and the pilot production.

2. Laser doping equipment

The newly developed laser doping technology has many advantages over the conventional doping technology. It can accurately control the heat input in the local region, form doped areas directly which could be operated at ambient temperature to reduce the thermal effect, and the processing is fast and simply, and more suitable for thin silicon substrates. The technology would be useful for the rear local doping, and the ablation of the dielectric passivation layer on the rear.

3. Contactless loading machine

3.1 Roller contactless loading schema is utilized to reduce the abrasion of cells on the convey belt, an automatic contactless wafer loading machine with a robotic arm to reduce the contact contamination. The flexible top robotic arm and a 6-axis wafer-sucking robot were equipped with an absolute encoder to record the operation and the location. The controller and the safety control module with high-speed CPU could ensure the operational accuracy and stability and the safety of the operator.

3.2 To decrease the abrasion of cells on the convey belt, an automatic contactless wafer loading machine with a robotic arm to reduce the contact contamination. The flexible top robotic arm and a 6-axis wafer-sucking robot were equipped with an absolute encoder to record the operation and the location. The controller and the safety control module with high-speed CPU could ensure the operational accuracy and stability and the safety of the operator.

3.3 The automation mainly incorporates the following four modules: 1) A roller contactless loading schema is utilized to reduce the contact contamination between the wafer and the rollers. Currently, the chain cleaning machine is connected to the rolling conveyer made out of special materials. The wafer outlet is equipped with two visual positioning and computation systems to acquire an accurate location of a wafer. Figure 2 illustrates a schematic of an automatic loading, in the chained cleaning machine.

3.4 Contactless suction eliminates wafer breakage and contamination from the roller and the wafers in contact. A contactless sucking device based on Bernoulli’s Principle is employed; the condensed air is exhausted through the gaps between the wafer and the sucker. The sucker works even on a rough wafer surface which a vacuum sucker is incapable of completing. This sucking device has three advantages: a) contactless suction eliminates wafer breakage and contamination, b) large contact area and a homogeneously applied force ensures a low breakage rate; c) a long service life.

2.5 Equipment Research Center

The core component of the laser doping equipment is the cleaning machine. 2) 2 high-precision and high-speed 6-axis robot arms are used alternatively as per the computational analysis. This scheme not only reduces the wafer breakage rate compared with the manual handling but also increases the speed of wafers being put into the box and . The margin of error on the positioning of a wafer into a box is ≤0.2mm. The repetition and the positioning precision of the robot arm are controlled within 0.01mm and 0.05mm respectively to comply with the higher throughput requirement of the cleaning machine.

3.3 A sucking device is employed to load the wafer. This method has been selected in order to reduce the abrasion and the contact contamination from the roller and the wafers in contact. A contactless sucking device based on Bernoulli’s Principle is employed; the condensed air is exhausted through the gaps between the wafer and the sucker. The sucker works even on a rough wafer surface which a vacuum sucker is incapable of completing. This sucking device has three advantages: a) contactless suction eliminates wafer breakage and contamination; b) large contact area and a homogeneously applied force ensure a low breakage rate; c) a long service life.

4) A vision system is required for high-speed positioning and in-line detection of the wafer breakage. The positioning precision needs to be within 0.02mm to accommodate the existing loading box and wafers, as well as the deformed box from long-term usage. Two industrial high-speed smart camera with 5M resolution are used as a part of the vision system. The physical camera presents the single-resolution size of 0.15mm. The imaging accuracy can reach up to 0.0218mm (0.175mm/8 = 0.0218mm) level if followed by sub-pixel imaging, and image detection & positioning algorithm.

3. Contactless loading machine

The EL defect-detection system can monitor and detect defects in cells using the EL imaging technique. Various types of defects can be accurately detected and sorted using this equipment - material defects such as dislocation, abnormal doping, and stacking fault; diffusion defects such as sheet resistance in-homogeneity; screen printing defects such as broken lines; firing defects such as the beltprint, and the contamination during the processing. The main purpose of the integration is to increase the cell yield, to enhance the sorting and to reduce the material consumption and the cost.

Prior to the automatic detection, workers manually detected and classified cell and module defects using the EL images. As the industry developed and grew, increasing quantity of cells and modules needed to be quality controlled and disadvantaged of manual handling such as the eye fatigue and the variance in classification among operators became increasingly pronounced.

The automatic EL defect-detection technique splits and extracts EL images followed by the defect analysis and detection. The automated analysis of a cell was cross-checked against the output of the cell. The imaging technique includes EL image capturing, antibarreling, the perspective transformation, gray scale correction and the segmentation of the captured EL image. This technique is capable of accurately detecting fragments, cracks and broken lines as shown in Figure 4.

The key to the automatized detection lies in the development of the software algorithm, in which an advanced algorithm and the intelligent-learning neural network play a pivotal role in the accuracy of the detection. The accuracy also depends on the input image quality - pixel, resolution, grayscale, noise, and stray light. The key algorithm code for the edge is shown below:
5. Automatic multi-busbar stringer

The automated multi-busbar stringer is capable of completing the soldering step automatically. The solar cell/cell string conveyor has been independently designed and optimized at the SKL PVST to ensure an accurate positioning of the solar cell and the solder. When compared with the conventional automated stringer, the multi-busbar stringer shows two key advantages - precise positioning of the round solder against the front and the rear busbars, and a high pulling force.

6. Summary

The rapid development of China’s PV industry necessitates the technology innovation and the cost reduction to continue its exponential growth. In turn, the technology innovation requires the development of appropriate PV equipment to accommodate the changing technologies in the manufacturing line. Under the directives of the Chinese government with programs such as “Internet +” and “made in China 2025 Plan”, PV manufacturers and PV equipment manufacturers are increasingly focusing on developing intelligent manufacturing lines which utilize the internet, an automatic control and the digital management.

PTP (Pattern Transfer Printing) technology for a novel selective emitter finger alignment

Hongshan Qi, Zhiqiang Ding, Xinmin Xiao

The Selective Emitter (SE) coupled with the Pattern Transfer Printing (PTP) technology enables narrow metal fingers to be printed precisely on the narrow mask pattern. PTP is a big breakthrough in SE fabrication R&D. To maximize the advantage of PTP and SE technologies, a new PTP technology that is suitable for narrow SE mask lines has been developed, and the metal fingers that are less than 40μm in width can be printed on mask lines that are less than 100μm wide. The height of metal fingers obtained was 12-16μm. ±15μm margin of error could shorten the width of mask lines by more than a half and lead to high resistance.

1. Background

PTP technology is an advanced contactless printing technique which has been demonstrated to be an effective technique to fabricate cost-effective solar cells. But the printing precision of the conventional PTP technology is incompatible with SE technology since its margin of error is too large and cannot accommodate the narrow.

2. Design of novel metallization pattern

PTP pattern was optimized with factors such as the diffusion resistance and the height to width ratio of the fingers in consideration. The analysis using software simulation showed that 120-130 was the optimal number of fingers for the highest solar cell conversion efficiency (Figure).

3. SE mask pattern with narrower fingers

The key point in the SE processing technique with narrow mask lines is to control the width of each mask line. The main purpose of the SE mask is to block the masked area from being etched in the following etching process. The conventional width of a SE mask line is between 200-300μm. Such mask line design has been developed for the screen printing methodology to align with the metal fingers. However, these relatively wide mask lines could potentially enlarge the low-resistance and high-recombination areas of SE cell, which would negate the

Figure 4
Solar cell automated defect detection result

Figure 5
Multi-busbar cell string (left) and the stringer (right)

Figure 1
Simulation of the finger pattern optimization

Figure 2
New busbar pattern
Compared with the screen printed cell, there are many advantages of the PTP printed cell; an expected efficiency gain of 0.1-0.2%, the Ag paste consumption reduction by more than 30%, the throughput increase to 1580 pcs/h, and the wafer breakage rate of less than 0.05%.

This PTP technology has a good compatibility with SE technology. The combined technology allows the width of the SE wafer mask to be reduced to 100-150µm; precision of the printing can be controlled within ±15µm; accurate printing of metal fingers on the mask fingers. The simulation predicts an efficiency gain of 0.1-0.2% using PTP SE technology compared with the conventional SE technology. Resultant efficiency from PTP technology can further be enhanced by coupling with multi busbars as it would reduce the collecting path of the electronic.

4. Development of SE with highly precise PTP technology

The aim is to develop an alignment technique of narrow fingers in SE and overprint the metallization paste on the pattern mask. The development of the highly precise pre-alignment unit could realize a precise imaging in the low-contrast SE mask fingers, and determine the precise position of the SE pattern on the solar cell via the computation of the images in place of the previous PTP pre-alignment module.

The difficult point in the recognition of the SE mask is the low contrast between the SE mask fingers and the etched regions on the SiNx-deposited solar cell surface. The contrast could be enhanced by increasing the light intensity incident on the solar cell surface and the auto-matching with the spectrum of incident light. The pre-alignment camera could recognize the narrower SE mask finger position to guarantee the successful execution of the optimized SE technique.

The SE mask recognition unit is small in size but has a high level of integration which incorporates five cameras to recognize the mask position with high precision. Different regions on the wafer captured by five cameras are shown in Figure 3; vertical line positions of the mask are recognized by camera 1 and camera 3 by verifying the distance of the outer two lines to the edge of the wafer. The distance between the mask line and the edge of the wafer in horizontal direction is checked by camera 2 and camera 4 and calculate the gap between the two lines. The rotation angle of the pattern onto the wafer can be confirmed by camera 1 and camera 5 along with the position recognition of other cameras. The composition of the SE mask pattern recognition unit is shown in Figure 4 where the cameras’ position corresponds to the capture points in Figure 3.

Based on the empirical analysis, the SE alignment unit was designed (Figure 5). Each camera on the unit has a light source which is located on the side at 35 degrees angle, and has four selective light sources at 4 different wavelengths to improve the recognition of fingers prior to the printing. Figure 6 shows the prototype of the SE alignment unit.

5. Summary

Compared with the screen printed cell, there are many advantages of the PTP printed cell; an expected efficiency gain of 0.1-0.2%, the Ag paste consumption reduction by more than 30%, the throughput increase to 1580 pcs/h, and the wafer breakage rate of less than 0.05%.

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The testing laboratory at the State Key Laboratory PV Science and Technology (SKL PVST) is comprised of characterization, simulation, module and system testing divisions, and provides testing and characterization services to R&D groups and the manufacturing department.

Silicon wafers and solar cells, including half-finished solar cells, are characterized in the characterization laboratory. The simulation laboratory optimizes each processing and characterization step involved in manufacturing a solar cell through simulation and analytical modelling, namely, Centaurus TCAD and Quokka. The module testing laboratory evaluates module reliability and performance - 175 tests which include thermal and chemical analysis are conducted. The system testing laboratory provides system testing service and performance analysis to Trina Solar system owners and stakeholders.
3.1 c-Si Solar Cell Characterization & Simulation

This laboratory develops testing and characterization methods suitable for silicon wafers, half-finished and completed solar cells, and provides technical services to other departments of Trina Solar.

3.1.1 Characterization

This group monitors and manages cell processing, provides testing services to the cell manufacturing line, and develops testing methods suitable for high-efficiency solar cells.

The main test items:

- HALM/IVT-IV curve
- IV curve or Suns-Voc on Sinton instrument
- Minority carrier lifetime measurement
- ECV curve
- Doped sheet resistance measurement
- PL/EL/Rs mapping

- QE spectrum response and reflectance
- 3D morphology
- SEM morphology with quantitative analysis
- Element composition measurement in EDX
- Sheet resistance and contact resistivity by TLM
- Coating thickness and reflective index measurement in Spectroscopic Ellipsometer
3.1.2 Simulation

Optical, thermal and electrical characteristics of silicon-based and compound solar cells are simulated in multi-dimensions using Centaurus TCAD and Quokka - both empirical and theoretical approaches are employed in developing a model. The group provides theoretically optimized models/scenarios to R&D groups, the pilot line and the manufacturing line within Trina Solar. It employs an independently developed 3D optical simulation tool based on Centaurus TCAD and Monte Carlo method, combined with QE spectral response and reflectance, it is an effective characterization method in predicting the short circuit current gain of an optically optimized processing step. In Figure 3, the measured reflectance and the simulated reflectance are compared and it demonstrates the proximity of the theoretical simulation to the actual measurement.

Various models are built for different cell structures using Centaurus TCAD and Quokka which significantly reduces the modeling difficulty and simplifies parameter-setting steps. In Centaurus TCAD, 2D and 3D models are constructed to describe mechanisms of the carrier generation, transportation and recombination. The power loss analysis of a solar cell under various operating conditions is the most useful aspect of the device simulation as reducing these power losses would lead to overall power gain in a solar cell.

Electrical schematics and analysis of finger bars are carried out using SPICE and nodal analysis. The nodal analysis computes the power loss due to the series resistance using the current flow rules in busbars and fingers. SPICE simulates a solar cell circuit by creating a series of micro-units to verify circuit operation.

3.2 Module Testing Laboratory

Module testing laboratory performs module reliability tests and solar cell materials’ physical and chemical tests. The laboratory has established a long-term strategic collaboration with credible accreditation and testing institutions both in China and overseas. Trina Solar was the first PV manufacturer to obtain UL CTDP (Client Test Data Program), and has also obtained WTMP (Witness Testing at Manufacturer’s Premises) accreditation from TUV Rheinland, and the Golden Sun Certificate accreditation from CGC.

In 2016, the laboratory has successfully been re-certified with CNAS, TUV-PTL, UL CTDP and WTMP. It also obtained CSA-WMT and CTF from TUV Rheinland – Trina Solar is the first PV manufacturer to obtain this certification.

175 tests focusing on module reliability, thermal analysis of PV materials, physical property of PV auxiliary materials, and chemistry measurements are carried out.

![Figure 3: Independently developed 3D optical simulation tool](image1)

![Figure 4: 3D models created by Centaurus TCAD and Quokka, recombination current analysis of a solar cell at various operating conditions](image2)

![Figure 5: Electrical simulation based on SPICE method](image3)
3.2.1 Module Reliability Testing Laboratory

Module reliability testing laboratory focuses on common reliability tests in IEC 61215, IEC 61730-2, and UL 1703, LID testing in IEC 62804 and other non-standard reliability tests. Test items are classified into five categories - electrical performance, safety, indoor accelerated aging in an environmental chamber, mechanical stress, and outdoor hot-spots. The laboratory updated its testing equipment in 2016 to comply with the international standard as set in IEC 61215 and IEC 61730.

Module Electrical Performance Test

Modules undergo various indoor accelerated aging tests, including performance under STC and NOTC, IV characteristics at low irradiance, and fitted temperature coefficients for Isc, Voc, and Pmax.

Module Safety Determination

Safety tests to determine the insulation between the internal electrical circuits and the metal frames are conducted. The accessibility of charged parts, the grounding continuity and the capability to withstand the fire hazards or flaming are some of the safety tests.

Indoor aging test in an environmental chamber

Aging tests to determine whether a module could withstand the thermal mismatch, fatigue, vapor ingress when subjected to a variety of rigid environmental conditions are carried out. Conditions include cyclic temperature variations, a long-term high-temperature and high-humidity exposure as well as a long-term exposure of EVA and backsheet to UV.

Mechanical tests

This testing group determines whether a module could withstand various stresses during transportation, installation, and in operation on field. Stresses on modules could be imposed by workers, environmental conditions, and support structures.

Conditions include cyclic temperature variations, a long-term high-temperature and high-humidity exposure as well as a long-term exposure of EVA and backsheet to UV.

Mechanical tests

This testing group determines whether a module could withstand various stresses during transportation, installation, and in operation on field. Stresses on modules could be imposed by workers, environmental conditions, and support structures.


3.2.2 Physical and Chemical Test Laboratory

Physical and chemical test laboratory conducts tests in accordance with IEC, SEMI, GB and other relevant industry standards to assess the reliability and the stability of PV materials used in manufacturing lines as well as in R&D programs.

Differential Scanning Calorimeter (DSC)

DSC tester monitors the temperature difference between the sample and the reference material as the temperature increases. It measures properties such as the degree of EVA cross-linking, the melting point of PV materials, enthalpy, glass transition temperature, and cold crystallization.

Water Vapor Permeability of backsheets

This test is to measure the water vapor permeability of the water-blocking materials such as PV backsheets, EVA, polyester films, and other soft packaging materials.

Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES)

Samples are transferred to the spray chamber and enter into the axis-directed tunnel in a form of gas gel and undergo stages of evaporation, atomization, ionization, and excitation in a high temperature and inert atmosphere where specific spectral lines that are characteristic of particular elements are emitted. Types of elements present in the sample are derived from the spectral lines emitted and the concentration of the element within the sample is inferred from the intensity of this emission.

Outdoors Hot-spot Test

The hot-spot test is performed to determine the module’s ability to withstand instantaneous and prolonged exposure to heat.
3.3 PV System Testing Laboratory

PV system testing laboratory consists of an electrical test laboratory, an outdoor power test laboratory, a power plant engineering test laboratory and an outdoor demonstration test laboratory. In 2015, the laboratory has passed the annual examination for CNAS, TUV-PTL, UL CTDP and WTMP, and has obtained the certification of CSA-WMT and CTF from TUV Rheinland – Trina Solar is the first PV manufacturer to obtain these certifications. The certification covers 87 test items from 6 PV-system related standards. Trina Solar is the only PV module manufacturer in PV industry to be CNAS certified in PV power plant engineering test and PV electrical component test (mainly a PV inverter).

3.3.1 Electrical Test Laboratory

Electrical test laboratory performs tests on PV components such as inverters and power distribution cabinets. In 2015, a number of high-precision test equipment from reputable manufactures was added to the laboratory. Over 30 tests can be performed including inverter conversion efficiency, static/dynamic MPPT efficiency, grid-connected PV power quality, power frequency withstand voltage, overvoltage and under-voltage protections. In particular, inverter performance at low-irradiance and/or high-temperature can be assessed to verify stable operation of a PV system over its lifetime. The quality and capability of this laboratory is comparable to those of domestic (Chinese) testing authorities.

3.3.2 Power Test Laboratory

Power test laboratory conducts module power related tests in accordance with IEC 61853. Key module materials such as the glass, the solder, solar cells, encapsulants, and backsheets are tested for its impact on module power generation; actual measured data in real-world operating conditions are gathered and analyzed, and the results and findings are provided to the module development team. This laboratory is capable of synchronously monitoring and measuring real-time module power in 150 channels for more than three months. Highly experienced staff members in PV power generation measurement & analysis have assessed more than 50 PV plants.
3.3.3 Power Plant Engineering Laboratory

Power plant engineering laboratory provides performance assessment and test service to power plant owners and managers. Key performance indicators such as PR (performance ratio), system power loss (AC/DC loss, mismatch loss, shading or dust loss, temperature-related loss), and power degradation are useful reference for PV power plants with a similar architecture. For PV plant developers and owners, these performance data would be critical to verify the financial viability of potential projects. The group is experienced in conducting system-related tests and analysis, and capable of providing consultation for maximum power plant project earnings.

3.3.4 Outdoor Demonstration Laboratory

Outdoor demonstration laboratory has been set up to assess the performance of PV modules and BOS components under typical climate conditions (i.e. hot & dry, hot & humid, cold & cloudy, and cold & sunny). Test sites include Changzhou representing the moderate climate, Xinjiang representing the dry desert climate, and Yunnan representing the plateau climate. A site representing the hot and humid climate is currently under construction.

DC and AC data are collected over long-term, and an in-depth computational analysis of PV modules and systems is carried out. The analysis includes module’s performance at low irradiance, aging of PV materials, system efficiency, current & voltage movement in relation to ambient temperature. Parameters relating to modules and system losses are referenced from PVsyst and PVsol. System design, PV power plant performance assessment, malfunction diagnosis and failure prediction are performed with an actual performance data taken from demonstration sites. Such studies are a valuable reference resource for the asset and investment management.
Chapter 4 Appendices

◆ 4.1 Achievements and Awards
◆ 4.2 Participation in National and International Projects
◆ 4.3 Co-Op Projects
◆ 4.4 Academic Exchanges
◆ 4.5 Patents
◆ 4.6 PV Standards
◆ 4.7 Published Papers
4.1 Achievements and Awards

On April 26th, 2016, an independently developed crystalline silicon IBC solar cell on a large-area 156x156mm² substrate obtained a world record conversion efficiency of 23.5%.

On August 12th, 2016, the Osaka Sangyo University’s solar cell, equipped with Trina Solar’s advanced Interdigitated Back Contact (IBC) solar cells and modules, won the championship of the 2016 FIA Solar Car Race.

On December 19th, 2016, the independently developed P-type mono-crystalline silicon solar cell obtained world record conversion efficiency 22.61%.

On June 8th, 2016, Dr. Pierre Verlinden was honored with the 2016 William R. Cherry Award in 43rd IEEE PVSC.

On October 18th, 2016, an independently developed high-efficiency Honey Plus multi-crystalline silicon solar module obtained a world record aperture efficiency of 19.86%.

On December 13th, 2016, the invention patent of interdigitated back contact solar cell fabrication method (No. of ZL201210141633.5) was honored with 18th China Patent Excellence Award.

4.2 Participation in National and International Projects

<table>
<thead>
<tr>
<th>Serial No</th>
<th>Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Certification Center research project – Key techniques for industrialization &amp; product testing of high efficiency anti-PID P-type crystalline silicon solar cells and modules</td>
</tr>
<tr>
<td>2</td>
<td>Collaborated with China General Certification Center, Yingli Solar and Product Supervision &amp; Inspection Center on the project – Research and development of test equipment for accelerated aging testing of PV modules</td>
</tr>
<tr>
<td>3</td>
<td>R&amp;D of dual glass solar modules with high performance and low cost N-type crystalline silicon solar cells and its industrialization</td>
</tr>
<tr>
<td>4</td>
<td>Collaborated with Changchun Institute of Applied Chemistry, Chinese Academy of Sciences, Nanjing University, Nankai University and North China Electric Power University on the key techniques of novel perovskite structured solar cell</td>
</tr>
<tr>
<td>5</td>
<td>Collaborated with the National University of Singapore on an advanced combination of extended indoor and outdoor PV module &amp; system testing across various climate zones</td>
</tr>
<tr>
<td>6</td>
<td>Collaborated with the Australian National University, the University of New South Wales, New South Wales Innovations Pty Limited on advanced surface and contact technologies for industrial silicon photovoltaics</td>
</tr>
<tr>
<td>7</td>
<td>Outdoor PID test</td>
</tr>
<tr>
<td>8</td>
<td>Developing equipment and process for tightly aligned finger printing on the next generation selective emitter lines for silicon solar cells</td>
</tr>
<tr>
<td>9</td>
<td>Research on optical two-dimensional crystal orientation detecting techniques for multi-crystalline silicon</td>
</tr>
<tr>
<td>10</td>
<td>Device physics and loss analysis for industry-level crystalline silicon solar cell</td>
</tr>
<tr>
<td>11</td>
<td>Research on enhanced spectral absorption of micro-nano resonant structure and its application on solar cells</td>
</tr>
<tr>
<td>12</td>
<td>Research on LID mechanism of crystalline silicon solar cells</td>
</tr>
<tr>
<td>13</td>
<td>Mechanical loading test failure analysis and countermeasures of crystalline silicon PERC photovoltaic devices</td>
</tr>
<tr>
<td>14</td>
<td>Research on key techniques of interdigitated heterojunction solar cell with back contact structures</td>
</tr>
</tbody>
</table>

List

1. On February 19th, 2016, Dr. Pierre Verlinden was honored with 2015 International Scientific Technology Cooperation Award of Jiangsu Province.
2. On March 3th, 2016, the invention patent of interdigitated back contact solar cell fabrication method received 13th Patent Golden Award of Changzhou.
3. On April 26th, 2016, an independently developed crystalline silicon IBC solar cell on a largearea 156x156mm² substrate obtained a world record conversion efficiency of 23.5%.
4. On May 25th, 2016, Dr. Zhiqiang Feng was honored with 2016 Willian R. Cherry Award in 43rd IEEE PVSC.
5. On June 8th, 2016, Dr. Pierre Verlinden was honored with 2016 William R. Cherry Award in 43rd IEEE PVSC.
6. On July 5th, 2016, Doumax dual glass solar module was the first to pass the latest accreditation criteria of ‘Top Runner’ Dual Glass Solar Module Technical Specifications.
7. On August 12th, 2016, the Osaka Sangyo University’s solar cell, equipped with Trina Solar’s advanced Interdigitated Back Contact (IBC) solar cells and modules, won the championship of ‘Dream Group’ in the 2016 FIA Solar Car Race.
8. On August 25th, 2016, Dr. Zhiqiang Feng was honored with 2016 AsiaSolar Top 10 PV Innovation Figure Award.
9. On October 18th, 2016, Trina Solar was honored with the 16th China Photovoltaic Conference Organization Contribution Award, and Dr. Qingzhong Zhu and Dr. Weiyan Duan was honored with Excellent Scientific Paper Award in the 16th China Photovoltaic Conference.
10. On October 18th, 2016, Dr. Zhiqiang Feng was honored with ‘outstanding contribution entrepreneur expert’ award by 16th China Photovoltaic Conference.
11. On October 18th, 2016, an independently developed high-efficiency Honey Plus multi-crystalline silicon solar module obtained a world record aperture efficiency of 19.86%.
12. On November 18th, 2016, Trina Solar was among the first batch in China to pass NIM (National Institute of Metrology) module power measuring uncertainty assessment certification.
13. On December 13th, 2016, the invention patent of interdigitated back contact solar cell fabrication method (No. of ZL201210141633.5) was honored with 18th China Patent Excellence Award.
14. On December 19th, 2016, the independently developed P-type mono-crystalline silicon solar cell obtained world record conversion efficiency 22.61%.

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4.4 Academic Exchanges

From January 28th to 29th, 2016, Dr. Pierre Verlinden attended 12th Workshop on the Future Direction of Photovoltaics held in Tokyo Institute of Technology, Japan, and delivered a presentation on ‘Challenges and Opportunities of High-Performance Solar Cells and PV Modules in Large Volume Production’.

On February 23rd, Jianmei Xu attended the workshop of National Renewable Energy Laboratory in US, and delivered a presentation on ‘The Reliability of Dual-Glass Module Designed for Harsh Climates.’

From February 27th to March 5th, 2016, Dr. Zhiqiang Feng attended 2016 PV EXPO conference held in Tokyo, and delivered a presentation on High-Efficiency and High-Reliability Anti-PID Solar Cells and Solar Modules.

From March 4th to 12th, 2016, Dr. Pierre Verlinden, Weivei Deng and Wenhao Cai attended 2016 SiliconPV Photovoltaic Workshop, Weivei Deng delivered a presentation on Development of High-efficiency Industrial p-type Multi-crystalline PERC Solar Cells with Efficiency Greater than 21%.

From March 16th to 17th, 2016, Dr. Pierre Verlinden was invited to attend Photovoltaic Solar Cell Technology Conference held in Kuala Lumpur of Malaysia, and delivered a presentation of The Prospect of Mass-Produced MultiCrystalline Cells above 20% Efficiency: How High Can p-TypeMultiGo.

From April 5th to 10th, 2016, Dr. Pierre Verlinden, Guanchao Xu and Feng Ye attended 43rd Photovoltaic Specialists Conference, Dr. Pierre Verlinden delivered a presentation on Mass Production of High-Efficiency p-Type PERC Solar Cell: How High Can p-Type Multi Go, and 40 Years of Development of IBC Silicon Solar Cells. Why is it Taking So Long?, and was honored with William R. Cherry Award. Guanchao Xu delivered a presentation on 6 Inch IBC Cells with Efficiency of 23.5% Fabricated with Low-Cost Industrial Technologies and Feng Ye delivered a presentation on 22.13% Efficient Industrial p-Type Mono PERC Solar Cell.

On June 17th, 2016, Dr. Pierre Verlinden visited Ohio State University, and delivered a presentation on 22.15% World Efficiency Record with Multi-crystalline p-Type Silicon Solar Cells: Closing the Gap with n-Type Monos.

From June 20th to 24th, 2016, Dr. Pierre Verlinden, Dr. Weiyuan Duan, Zhonglan Li, Shengcheng Zhang, Shu Zhang, Huijun Zhu and Jing Mao attended 33rd European Photovoltaic Solar Energy Conference. Dr. Pierre Verlinden delivered a presentation on ‘Perspectives for Cost Decline in the PV Industry’ in IEA PVPS Task4, Weiyuan Duan delivered a presentation on ‘A Route towards High Efficiency n-type PERT Solar Cells, Zhonglan Li delivered a presentation on Pilot Production of 6” IBC Solar Cells Yielding A Median Efficiency of 23% with A Low-Cost Industrial Process, Shu Zhang delivered a presentation on Low Temperature Conductive Film (CF) Interconnection Process for PV Modules.

From August 25th to 26th, 2016, Dr. Zhiqiang Feng, Jianmei Xu and Yue Zong attended 12th China SoG Silicon and Solar Cells?.

From September 29th to October 1st, 2016, Guanchao Xu was invited to attend 2016 Photovoltaic Industry Workshop held in Sungkyunkwan University in Korea, and delivered a presentation on High-Efficiency Approach in Trina Solar.

From October 1st to 7th, Hui Shen attended SANYU-PV 2016 Workshop held in Japan, and delivered a presentation on Opportunity and Challenge: >21% Large-Area n-Type PERT Bifacial Solar Cells in Research and Production.

From October 8th to 16th, Shuya Ye attended 9th International Crystalline Silicon Solar Cell Workshop & 3rd Silicon Material Workshop, and delivered a presentation on The Numerical Simulation of Silicon-Crystalline Growth.

From October 14th to 18th, Dr. Zhiqiang Feng, Dr. Pierre Verlinden, Dr. Zhen Zhang, Dr. Zhen Xiong, Dr. Qiangzhong Zhu, Dr. Weiyuan Duan and et al (17 attendees in total) attended 16th China Photovoltaic Conference (CPCVC16), Trina Solar was honored with Organizational Contribution Award, Dr. Qiangzhong Zhu and Dr. Weiyuan Duan were honored with Excellent Scientistic Paper Award, Dr. Zhen Xiong, Dr. Yifeng Chen and other 12 attendees delivered 14 presentations.

On October 29th, Dr. Zhiqiang Feng and Dr. Pierre Verlinden attended 3rd Asia Photovoltaic Exhibit held in Singapore, Dr. Zhiqiang Feng delivered a presentation of Multi-crystalline Silicon Solar Module with Aperture Efficiency of 19.86%, Dr. Pierre Verlinden delivered a presentation on Will We Have > 22% Efficient Multi-crystalline p-Type Silicon Solar Cells?.

From October 19th to 21th, Dr. Zhiqiang Feng and Dr. Pierre Verlinden attended China Photovoltaic Conference & Exhibit held in Beijing, Dr. Zhiqiang Feng delivered a presentation on The PERC Solar Cell Technology from Laboratory to Industrialization, Dr. Pierre Verlinden delivering a presentation on Will We Have > 22% Efficient Multi-crystalline p-Type Silicon Solar Cells?.

On November 25th, Dr. Zhiqiang Feng, Jianmei Xu, Dr. Qiangzhong Zhu and et al attended 12th China SoG Silicon and PV Power Conference (CSPF), and delivered a series of presenta-
## 4.5 Patents

In 2016, 106 patents were filed. 3 were Patent Cooperation Treaty (PCT), and 48 were invention patents. 97 patents were approved this year, of which 38 patents were invention patents.

Cumulatively, as of December, 2016, 1317 patents have been filed by Trina Solar and of those, 597 were invention patents. With 747 valid patents and 220 valid invention patents, Trina Solar still holds the leading position amongst Chinese PV companies in number of valid invention patents held.

<table>
<thead>
<tr>
<th>No.</th>
<th>Invention Title</th>
<th>Invention No.</th>
<th>Authorized date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sheet metal battery positive electrode printing method and printing apparatus</td>
<td>ZL20141021773.8</td>
<td>2016/01/13</td>
</tr>
<tr>
<td>2</td>
<td>Method of preventing harmful polarization of crystalline silicon solar modules and the black line phenomenon occurs</td>
<td>ZL201210293067.X</td>
<td>2016/01/20</td>
</tr>
<tr>
<td>3</td>
<td>Heterojunction solar cell and preparation method using a mask width</td>
<td>ZL201410217097.1</td>
<td>2016/01/20</td>
</tr>
<tr>
<td>4</td>
<td>Upper and lower electrode structures of solar cells</td>
<td>ZL201210524975.5</td>
<td>2016/02/10</td>
</tr>
<tr>
<td>5</td>
<td>A power differential PV maximum power point tracking method based on</td>
<td>ZL201410476803.4</td>
<td>2016/02/10</td>
</tr>
<tr>
<td>6</td>
<td>Renewable Energy-powered street light system</td>
<td>ZL201310631186.6</td>
<td>2016/03/02</td>
</tr>
<tr>
<td>7</td>
<td>Full back electrode of the solar cell and method of making the full back electrode of solar cell</td>
<td>ZL201310635112.X</td>
<td>2016/03/02</td>
</tr>
<tr>
<td>8</td>
<td>Volume resistivity and sheet resistance of the converter calibration device and calibration method</td>
<td>ZL201410217300.5</td>
<td>2016/03/23</td>
</tr>
<tr>
<td>9</td>
<td>A photovoltaic roofing assembly structure and mounting structure</td>
<td>ZL201310260249.1</td>
<td>2016/04/06</td>
</tr>
<tr>
<td>10</td>
<td>A method of increasing the emitter system selection process method using a mask width</td>
<td>ZL201410135833.7</td>
<td>2016/04/06</td>
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<tr>
<td>11</td>
<td>Folding assembly</td>
<td>ZL201210134604.1</td>
<td>2016/04/06</td>
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<tr>
<td>12</td>
<td>Improve the boron-doped P-type silicon solar cell apparatus and methods of using light-induced attenuation</td>
<td>ZL201410447693.4</td>
<td>2016/04/06</td>
</tr>
<tr>
<td>13</td>
<td>Local solar cell doping methods</td>
<td>ZL201410277487.8</td>
<td>2016/05/11</td>
</tr>
<tr>
<td>14</td>
<td>A poppet photovoltaic cells parallel resistance method</td>
<td>ZL201310260236.4</td>
<td>2016/05/25</td>
</tr>
<tr>
<td>15</td>
<td>Heterojunction cells helps to reduce the number of positive gate line and its preparation method</td>
<td>ZL201410393187.6</td>
<td>2016/05/25</td>
</tr>
<tr>
<td>16</td>
<td>Micro-concentrating photovoltaic solder strip</td>
<td>ZL201310358556.3</td>
<td>2016/06/15</td>
</tr>
<tr>
<td>17</td>
<td>N-type doped polycrystalline silicon hydrogen passivation of heterojunction solar cell device</td>
<td>ZL201310354676.6</td>
<td>2016/06/29</td>
</tr>
<tr>
<td>18</td>
<td>Silicon etching and wet etching equipment</td>
<td>ZL201410075181.4</td>
<td>2016/07/13</td>
</tr>
</tbody>
</table>
4.6 PV Standards

As of December 2016, SKL PVST has participated in 64 standards. 45 standards have been published including 10 leaded standards. 14 standards under preparation include 1 IEC standard, 4 SEMI standards, 5 national standards and 4 industry standards.

<table>
<thead>
<tr>
<th>No.</th>
<th>Standard Name</th>
<th>Classification</th>
<th>Number</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The Technology Code in Integration of Building and Photovoltaic</td>
<td>Engineering construction department, provincial standard</td>
<td>DGJ32/JT 2009</td>
<td>Published on Nov. 10th, 2009, implemented on Jan 1st, 2010</td>
</tr>
<tr>
<td>2</td>
<td>Icon atlas of «Building integrated solar energy PV system design and installation»</td>
<td>National construction standard</td>
<td>10J108-S</td>
<td>Published on Jan. 6th, 2010, implemented on Mar. 1st, 2010</td>
</tr>
<tr>
<td>3</td>
<td>Technical code for application of solar photovoltaic system of civil buildings</td>
<td>Engineering construction department, /industrial standard</td>
<td>JGJ203-2010</td>
<td>Published on Mar. 18th, 2010, implemented on Aug. 1st, 2010</td>
</tr>
<tr>
<td>4</td>
<td>Code for operation and maintenance of building mounted photovoltaic system</td>
<td>Engineering construction department, /industrial standard</td>
<td>JGJ/T264—2012</td>
<td>Published on Dec. 26th, 2011, implemented on May 1st, 2012</td>
</tr>
<tr>
<td>7</td>
<td>Cross-linking degree test method for Ethylene-Vinyl Acetate applied in photovoltaic modules—Differential Scanning Calorimetry (DSC)</td>
<td>Regional standard/cross-strait common standard</td>
<td>GT 007-2012</td>
<td>Published in 2012</td>
</tr>
<tr>
<td>8</td>
<td>Building Integrated Photovoltaic (BIPV) modules nominal operating cell temperature test methods</td>
<td>Regional standard/cross-strait common standard</td>
<td>GT 008-2012</td>
<td>Published in 2012</td>
</tr>
<tr>
<td>9</td>
<td>Tinted ribbon for solar cell</td>
<td>Local standards</td>
<td>DB 32/T2176-2012</td>
<td>Published on Dec. 28th, 2011, implemented on Feb. 28th, 2013</td>
</tr>
<tr>
<td>10</td>
<td>Specification for package protect for PV module</td>
<td>SEMI standard</td>
<td>PI44-0513</td>
<td>Published on Jul. 19th, 2013, implemented on May 1st, 2014</td>
</tr>
<tr>
<td>11</td>
<td>VA content measurement in EVA of PV modules - TGA/Vinyl Acetate (VA) content test method for Ethylene-Vinyl Acetate (EVA) applied in photovoltaic modules - TGA</td>
<td>SEMI standard</td>
<td>PI45-0513</td>
<td>Published in May, 2013</td>
</tr>
<tr>
<td>12</td>
<td>Laminated solar PV glazing materials in building</td>
<td>National standard</td>
<td>GB 29551-2013</td>
<td>Published on Jul. 19th, 2013</td>
</tr>
<tr>
<td>13</td>
<td>Sealed insulating solar PV glass unit in building</td>
<td>National standard</td>
<td>GB/T 29759-2013</td>
<td>Published on Sep. 18th, 2013, implemented on Jun. 1st, 2014</td>
</tr>
<tr>
<td>14</td>
<td>Ethylene-vinyl acetate copolymer (EVA) film for encapsulant solar module</td>
<td>National standard</td>
<td>GB/T 29848-2013</td>
<td>Published on Nov. 12th, 2013, implemented on Apr. 15th, 2014</td>
</tr>
<tr>
<td>15</td>
<td>Crystalline silicon photovoltaic (PV) modules - Design qualification and type approval</td>
<td>PV industry union</td>
<td>CPIA 001-2013</td>
<td>Published on May 10th, 2013, implemented on Aug. 1st, 2013</td>
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</table>

45 published standards (10 guided standards)

<table>
<thead>
<tr>
<th>No.</th>
<th>Invention Title</th>
<th>Classification</th>
<th>Number</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction</td>
<td>PV industry union standard</td>
<td>CPIA 003-1-2013</td>
<td>Published on May 10th, 2013, implemented on Aug. 1st, 2013</td>
</tr>
<tr>
<td>17</td>
<td>Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing</td>
<td>PV industry union standard</td>
<td>CPIA 003-2-2013</td>
<td>Published on May 10th, 2013, implemented on Aug. 1st, 2013</td>
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<tr>
<td>18</td>
<td>Terrestrial crystalline silicon photovoltaic (PV) modules performance requirements in multiple climates Part 1: Hot-Dry climate condition</td>
<td>Technical specification</td>
<td>CQC3303-2013</td>
<td>Published and implement on May 20th, 2013</td>
</tr>
<tr>
<td>22</td>
<td>Vinyl Acetate (VA) content test method for Ethylene-Vinyl Acetate (EVA) applied in photovoltaic modules-TGA</td>
<td>Regional standard/cross-strait common standard</td>
<td>GT 030-2014</td>
<td>Published in 2014</td>
</tr>
<tr>
<td>24</td>
<td>Ethylene vinyl acetate (EVA) interlayer for building mounted photovoltaic module</td>
<td>Industrial standard</td>
<td>JG/T459-2014</td>
<td>Published on Sep. 29th, 2014, implemented on Apr. 1st, 2014</td>
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<tr>
<td>26</td>
<td>Crystalline silicon PV cells manufacturing worker</td>
<td>Occupational skills standard</td>
<td>Published in 2014</td>
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<tr>
<td>27</td>
<td>Crystalline silicon PV cells manufacturing worker</td>
<td>Occupational skills standard</td>
<td>Published in 2014</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Specification for impurities in polyethylene packaging materials for polysilicon feedstock</td>
<td>SEMI standard</td>
<td>SEMI PV56-0215</td>
<td>Published in Jan, 2015</td>
</tr>
<tr>
<td>29</td>
<td>Test method for in-line monitoring of flat temperature zone in horizontal diffusion furnace</td>
<td>SEMI standard</td>
<td>SEMI PV53-0514</td>
<td>Published in Jan, 2014</td>
</tr>
<tr>
<td>30</td>
<td>Terminology for Back Sheet for Crystalline Silicon Terrestrial Photovoltaic (PV) Modules</td>
<td>National standard</td>
<td>GB/T 31034-2014</td>
<td>Published in Jul, 2014</td>
</tr>
<tr>
<td>31</td>
<td>Specification for Ultra-thin glasses used for photovoltaic modules</td>
<td>SEMI standard</td>
<td>SEMI PVE3-0215</td>
<td>Published in Feb, 2015</td>
</tr>
<tr>
<td>32</td>
<td>Test method for determination of total carbon content in silicon powder by infrared absorption after combustion in an induction furnace</td>
<td>SEMI standard</td>
<td>SEMI PVE9-0215</td>
<td>Published in Jan, 2015</td>
</tr>
<tr>
<td>33</td>
<td>Specification for framing tape for PV modules</td>
<td>SEMI standard</td>
<td>SEMI PVE6-0215</td>
<td>Published in Jan, 2015</td>
</tr>
<tr>
<td>34</td>
<td>Terminology for back contact PV cell and module</td>
<td>SEMI standard</td>
<td>SEMI PVD2-0215</td>
<td>Published in Feb, 2015</td>
</tr>
<tr>
<td>35</td>
<td>Vinyl Acetate (VA) content test method for Ethylene-Vinyl Acetate (EVA) applied in photovoltaic modules-TGA</td>
<td>National standard</td>
<td>GB/T 31984-2015</td>
<td>Published in Sep, 2015</td>
</tr>
</tbody>
</table>
In 2016, 36 papers were published. 23 were conference papers presented at international conferences such as SiliconPV, Institute of Electrical and Electronics Engineers (IEEE) Photovoltaic Specialists Conference, and European Photovoltaic Solar Energy Conference & Exhibition (EU PVSEC).

Scientific Paper List

01. Yingbin Zhang, Jiahua Tao, Yifeng Chen, Zheng Xiong, Ming Zhong, Zhiqiang Feng, Pingxiong Yang, Junchao Chu, A large-volume manufacturing of multi-crystalline silicon solar cells with 18.8% efficiency incorporating practical advanced technologies; Royal Society of Chemistry.


03. Jian Sheng, Wei Wang, Shengzhou Yuan, Wentao Cai, Yun Sheng, Yifeng Chen, Jianing Ding, Yingyi Yuan, Zhiqiang Feng, Pierre J. Verlinden, Development of a large-area n-type PERT cell with high efficiency of 22% using industrially feasible technology; Solar Energy Materials & Solar Cells.


07. Qiuxiang He, Jingwei Li, Jifei Sun, Xiaolong Bai, Zhen Xiong, Jian Chen, Effect of Sn Doping on Dislocation and Minority Carrier Lifetime of Directional Solidified mc-Si; Journal of Synthetic Crystals.
08. Wenzhu Liu, Liping Zhang, Renfang Chen, Fanying Meng, Wanwu Guo, Jian Bao, and Zhengxin Liu; Underdense a-Si:H film capped by a dense film as the passivation layer of a silicon heterojunction solar cell; AIP Journal of Applied Physics.

09. Kun Ding, Siyu Qin, Li Feng, Quanxin Zhai, Xiang Wang, Jingwei Zhang, Jing Mao; Development of an outdoor photovoltaic module test platform; IET Power Electronics.

10. Kun Ding, Li Feng, Siyu Qin, Jing Mao, Jingwei Zhang, Xiang Wang, Tao Peng, Quanxin Zhai; The Influence of Changing PV Array Interconnections under a Non-uniform Irradiance; Journal of Power Electronics.

11. Kun Ding, Hongye Gu, Fudong Chen, Yuanliang Li, Jing Mao, Jingyu Jiang; Research on the output characteristics of TCT-structured photovoltaic arrays under inhomogeneous irradiance; Renewable Energies.

12. Z. Zhang, L. Wang, S. Kurzt, J. Wu, P. Quan, R. Sorensen, S. Liu, J.B. Bae, Z.W. Zhu; Operating temperatures of open rack installed photovoltaic inverters; Solar Energy.

13. Zhen Zhang, Lei Wang, Yifan Cai, Kun Ding, Peng Quan, Jianmei Xu; Research on the photovoltaic bypass diodes under inhomogeneous irradiance; Acta Energiae Solaris Sinica.


15. Liping Zhang, Wenzhu Liu, Wanwu Guo, Jian Bao, Xiaoyu Zhang, Jinlin Liu, Dongliang Wang, Fanying Meng, and Zhengxin Liu; Interface processing of amorphous-crystalline silicon heterojunction prior to the formation of amorphous-to-crystalline transition phase; 43rd IEEE Photovoltaics Specialists Conference, Portland, OR, United States, 5-10 June 2016.


17. Guanchao Xu, Yang Yang, Xueling Zhang, Shu Chen, Wei Liu, Yan Chen, Zhiqiang Zhao, Li Feng, Pietro P. Altermatt, Pierre J. Verlinden, Zhiqiang Feng; 6 inch IBC cells with efficiency above 23.5% fabricated with low-cost industrial technologies; 43rd IEEE Photovoltaics Specialists Conference, Portland, OR, United States, 5-10 June 2016.

18. Weiyuan Duan, Shengzhao Yuan, Yun Sheng, Yifeng Chen, Yang Yang, Pietro P. Altermatt, Pierre J. Verlinden, Zhiqiang Feng; 20.8% PERC solar cell on 156 mm × 156 mm multi-crystalline substrate; 43rd IEEE Photovoltaics Specialists Conference, Portland, OR, United States, 5-10 June 2016.

19. Kun Ding, Siyu Qin, Li Feng, Quanxin Zhai, Xiang Wang, Tao Peng, Quanxin Zhai, Jinlin Liu; Development of high-efficiency industrial p-type multi-crystalline PERC solar cells with efficiency greater than 22%; SiliconPV 2016, the 6th International Conference on Silicon Photovoltaics, Chambery, France, 9-10 March 2016.

20. Wenhao Cai, Shengzhao Yuan, Yun Sheng, Weiyuan Duan, Zigang Wang, Yifeng Chen, Yang Yang, Pietro P. Altermatt, Pierre J. Verlinden and Zhiqiang Feng; 22% efficiency n-type PERC solar cell; SiliconPV 2016, the 6th International Conference on Silicon Photovoltaics, Chambery, France, 9-10 March 2016.


23. Chenguang Sun, Liping Zhang, Renfang Chen, Fanying Meng, Impact of the micro structures of a-Si window layer on the crystalline silicon heterojunction solar cells; Photovoltaic Conference and Exhibition of China 2016 & 16th China Photovoltaic Conference.

24. Yangyang Zhao, Liping Zhang, Renfang Chen, Zhen Xiong, Zhiqiang Feng, Research of wind and snow load resistant performance of PV modules; Photovoltaic Conference and Exhibition of China 2016 & 16th China Photovoltaic Conference.