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HIT PV Module Performance Research for an Improvement of Long-term Reliability: A Review

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ABSTRACT: We report finding ways to improve the long-term reliability of PV module including the heterostructure with the intrinsic thin layer (HIT) solar cell. We point out the stability of the products of Panasonic HIT cell. We account for a brief description of the module manufacturing process to investigate the issues of each process and analyze the causes. We carried out the silicon PV module of the glass to glass type under the damp heat test around 1000 hours. However, it degraded around 7% of PV module power after 300 hours exposure in comparison with the initial status (Initial: 12.7 Watt). We investigated possible cause and solutions for the module performance to develop the long-term reliability.

Key words: PV module, Reliability, HIT, Long-term lifetime, High-efficiency

1. Introduction: importance of PV technologies and status

Photovoltaic (PV) converts sunlight directly into electrical energy, and its structure is simple, safe, and little impact on the environment[1]. Solar cell technology goes beyond clean energy and has a significant effect on the various categories. Technical classification of photovoltaic power generation has divided into polysilicon (Poly-Si), ingot, wafer, solar cell, solar cell module and balance of system, which are raw materials of the solar cell when the crystalline silicon solar cell is used. We are focusing on developing solar PV system cost reduction as a key issue for mass supply. The development of the crystalline silicon solar cell technology has been proceeding in the direction of low cost and high efficiency to achieve high-quality performance. We investigated the technological trends related to high-efficiency solar cells and discussed the stability of Panasonic HIT solar cell, that is one of high-efficiency silicon solar cells.

Fig. 1 presents the status of mass production companies of cell and module efficiency for high performance silicon solar cells. Trina Solar set a new efficiency record of 22.6% (total area: 243.23 cm^2) for the high-efficiency p-type mono-crystalline silicon (c-Si) solar cell of advanced passivated emitter and rear cell (PERC) technology[2]. SunPower Corporation is entering the ultra-high efficiency solar cells with interdigitated back contact (IBC) structure. They have achieved of a 25.2% efficiency in the cell-level (module efficiency of 22.8%), achieving a reduction in manufacturing cost by replacing the high quality, expensive FZ silicon substrate with the CZ substrate since 2005[3]. The world best conversion efficiency of the mono-crystalline silicon solar cell is 25.6% (total area: 143.7 cm^2) obtained by a back contact HIT solar cell of Panasonic in 2014, and then achieved the world best module efficiency of 23.8% in 2016[4]. Kaneka Corp has realized the world's highest-efficiency (26.33%) crystalline silicon solar cell with a practical size (180 cm^2) by combining heterojunction and back contact technologies[5]. They announced that the conversion efficiency of its crystalline silicon photovoltaic module had reached 24.37% (Oct. 27. 2016).

So far, we investigated on the structure of the solar cell having a high-efficiency. The features of these solar cell structures are the absence of a front grid pattern and have the heterojunction structure. Among them, Panasonic HIT solar cell is still capable of the mass production because of the low-temperature process, a shorter process time, and the solar cell of similar structure that we are studying. In this article, we

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will discuss the reliability issues related to silicon heterojunction solar cells regarding both sides (the cell and module). Here we decided it as Panasonic HIT solar cell because it is similar to the solar cell structure, which we are studying.

Here, the primary strategy to approach the efficiency stability of the solar cell in SHJ has not changed such as the improving the characteristics of TCO layers, optimizing the grid electrode to suppress the shadow and resistance loss, and optimizing the resistance loss as shown in Fig. 2. TCO layers play a crucial role in electrodes and anti-reflection coating films for SHJ solar cells[6]. For a good output performance of SHJ solar cells, it is quite important of these layers (in the case of back reflector, lower absorption in the near-infrared region because of free carrier absorption). Carrier concentration must be as small as possible to reduce the absorption while maintaining the low resistivity[7]. It also satisfied the high mobility with the proper deposition process. We should design and optimize for improving the electrical and optical properties. Therefore, it enhanced the spectral response at near infrared region from the reduction of carrier concentration.

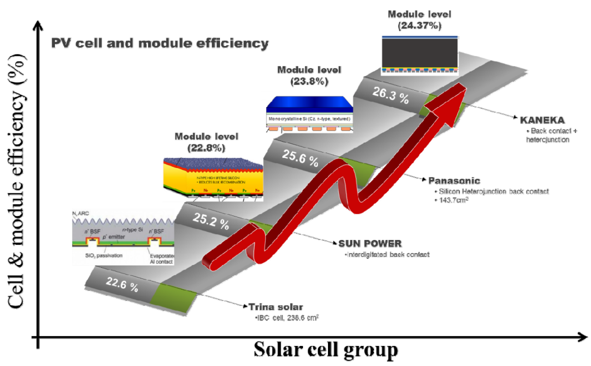


Fig. 1. Status of mass production companies for high-efficiency silicon solar cells

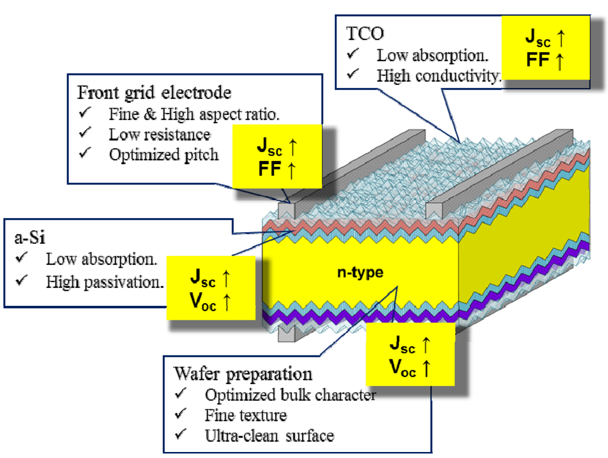


Fig. 2. A schematic diagrams of elementary strategies of SHJ cell stability issue (Panasonic HIT cell)

The silver paste can take a process at a low temperature for SHJ solar cell and has a relatively high resistivity in comparison with the conventional solar cells as well as expensive materials[8]. Therefore, it has continuously developed to minimize the electrical loss and shadowing loss at the grid pattern and need to study about the balanced the long-term reliability including the electrical properties having a low-cost material. The characteristics of a-Si layers are related to the resistance loss in SHJ solar cells. The intrinsic layer (i-layer) requires reducing the defect for surface passivation at the interface. However, it was an inevitable the resistive loss within i-layer. As a result, we need to improve the better deposition process and interfaces, and optimization of i-layer quality.

For increasing request in reliability, it is a necessary to demonstrate that high-efficiency HIT module shows high potential induced degradation (PID) resistance as originally designed[9]. We give an account of increasing high efficiency and reliability at the same time to maximize the lifetime power generation. For the normal cells, the insulating anti-reflection layer covered on the front surface and then the electrical charges can accumulate on the cell surface, resulted in the output power degradation. The HIT solar cell did not collect the charges because of TCO without insulating characteristics[10]. All HIT PV modules have exhibited no sign of degradation under several PID tests. Despite that; it still has another problem apart from the long-term reliability. So far, we discussed the efficiency stability of the HIT cell. We will explain the key issues of PV module manufacturing and module materials for the module balance.

2. Overview of manufacturing technology, material, and loss characteristics of solar cell module

2.1 The manufacturing technology of PV module process

The solar cell is a power generation system that converts infinite, pollution-free solar energy directly into electric energy. Since the voltage required from one cell is minuscule, about 0.6 to 0.7 V, it is used in series connection to enhance the required voltage[11]. The electrode portion connecting the cells is referred to as an interconnect ribbon, and structure in which a plurality of battery cells are connected to each other to obtain an appropriate electromotive force referred to as a photovoltaic module. To generate a positive output, several solar cells connected to perform processes such as tabbing & string, lamination, curing, and assembly, as shown in Fig. 3.

The module consists of solar cell arrayed to a certain capacity and then packaging with tempered glass, encapsulant, a back sheet, Al frame, and the solar module is as shown in Fig. 4. At this time, the capacity of general solar cell module has an output of 250 ~ 320 W per standard module as of 2016[12]. First, Tabbing refers to the process of aligning solar cells and metal electrode lines (ribbons) in a row using a heat source. Tabbing determines the quality of the module as an important factor. To smooth, the flow of current, solar cell electrodes used Ag paste to manufacture solar cells. Ribbon metal electrodes made of SnPb alloy surrounding Cu electrodes. When the solar cell module made by using SnPbAg paste on the electrode of the solar cell, the solar cell is connected by soldering, but the resistance of the ribbon electrode itself and the series resistance of the connection portion between the electrode and the cell increased, the efficiency of the module decreases.

The performance of the solar cell module varies depending on the kind of material used and the manufacturing method used in the production process so that it is necessary to select an optimal material for manufacturing the module and a proper manufacturing method. Among this equipment and approaches, Tabbing & String process connecting cells and cells is becoming more important. The series resistances of the whole module changes depending on the characteristics of the used metal, the characteristics of solder paste for interconnection and the manufacturing method. The efficiency of solar cells has been increasing steadily since the early 1970s through intensive R&D and investment, but the module manufacturing technology is less than that. In particular, a new solar cell structure for high efficiency such as an interdigitated back contact c-Si solar cell or a-Si/c-Si heterojunction solar cell has developed, but the effect of general module manufacturing technology has not maximized.

Therefore, it is necessary to secure the production techniques

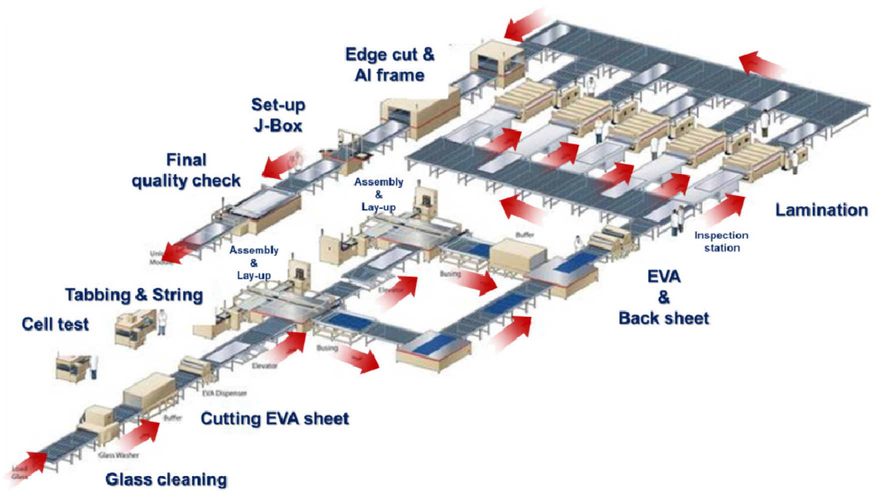
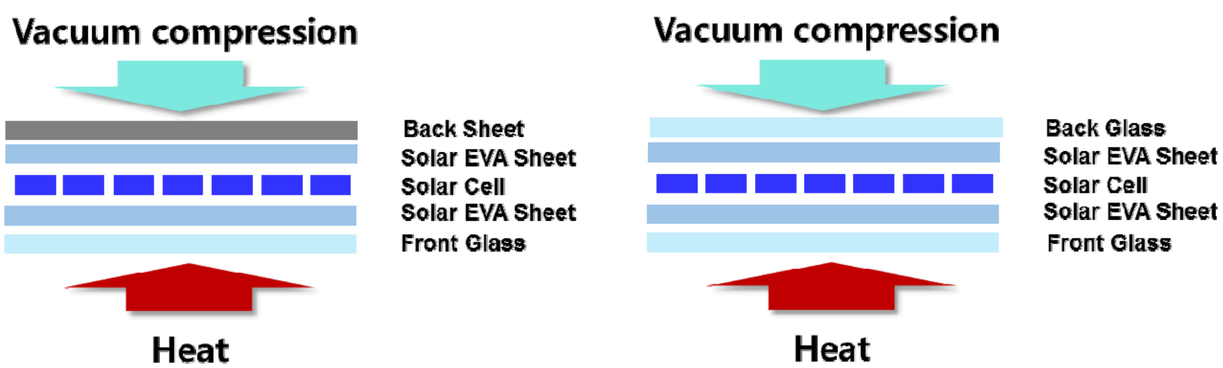


Fig. 3. Schematic of PV module process



(a) (b)

Fig. 4. Solar cell module structures with (a) back sheet, (b) Glass/Glass type

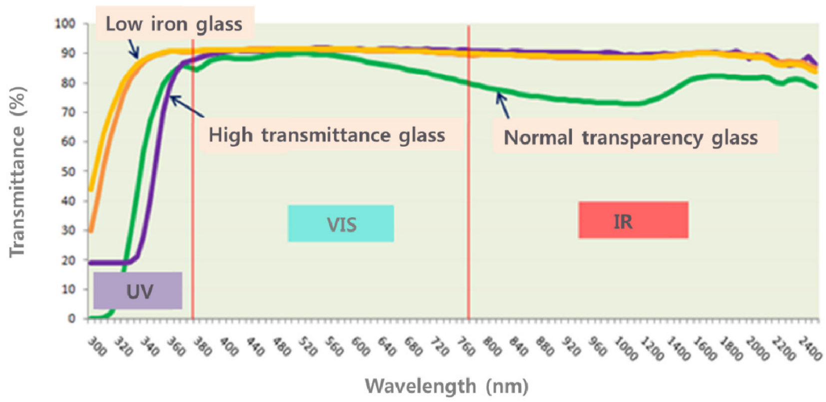


Fig. 5. The transmittance of glass at the wavelength from 300 nm to 2400 nm

and competitiveness through the development of module technology for the high-efficiency solar cell. The initial installation cost of photovoltaic power accounts for more than 50% of solar cell module, 20% of photovoltaic power generation equipment and 30% of another installation cost[13]. The manufacturing method of the solar cell module and systematically applying the mass production system by developing the material can lower the production cost and reduce the power generation cost of the photovoltaic power generation system. In the end, reliable module fabrication is feasible. It is necessary to develop the yield improvement which is related to the practical Pb-free ribbon and the contactless soldering for the module production.

2.2 PV module materials

So far, we investigated the critical issues of the solar cell module. Now we are describing the elements of PV module. The cover glass of the solar cell module consists of a low iron tempered glass having excellent light transmittance as shown in Fig. 5. Silicone resin, PVB, and EVA have used as the encapsulant materials. Silicon resin is mainly used to fabricate the solar cell module at the first time. However, it takes the time to prevent air bubbles and maintain the uniformity caused by up and down of moving the solar cells and is recently used in EVA because of moisture ingress. Most of the back sheet material is applied PVF covered with aluminum foil to increase the moisture resistance, EVA widely employed in recent years.

Silicone, polyurethane, polysulfide, and butyl rubber as sealant materials, but butyl rubber is frequently in use regarding reliability. The sealing material is in use for sealing the outgoing portion of the electrode lead, or the end of the module and currently Butyl rubber products as the tape form have widely used. The frame for the end of the solar module stands on the basis using the aluminum materials, but sometimes a rubber material is in use as the frame. The solar cells of wrong output make to find in the process of cell selection and then connected to each other with the wire. Terminal box, bypass diodes, and connectors are manufacturing after lamination and curing processes for the module assembly.

The SHJ module process is very similar to a conventional crystalline silicon module, except that the SHJ cell cannot perform the soldering step[14] because the cell treatment temperature may be too high. Thus, the strings and tabs carried out with a conductive adhesive (CA), which cured during the module lamination step. Conductive adhesives are more expensive than regular silver halide. At the same time, the resistance of the conductive adhesive is more important than regular solder. The back sheet assumed to combine a standard Tedlar s-Polyester-Polyamide (TPA) back sheet and an aluminum foil to ensure performance stability and moisture-related degradation of the SHJ module[15].

Solar cell metallization focuses on two aspects of reducing material consumption and replacing expensive metallization materials[16]. If the HIT solar cell is applicable, the reduction in the use of silver can be significant cost savings. However, copper is much easier to oxidize than silver, and diffusion of copper into the silicon substrate is problematic because copper atoms diffused into silicon can negatively influence the performance through a variety of mechanisms as shown in Fig. 6. The nickel barrier layer to solve this problem can prevent copper diffusion, but electroplating will thin the film to prevent oxidation. The metal contact wire is dried and cured to reduce copper oxidation in a nitrogen atmosphere[17].

Printed copper bus bars printed on SiNx ARCs and cured at low temperatures. <10 ppm Temperature in an oxygen atmosphere

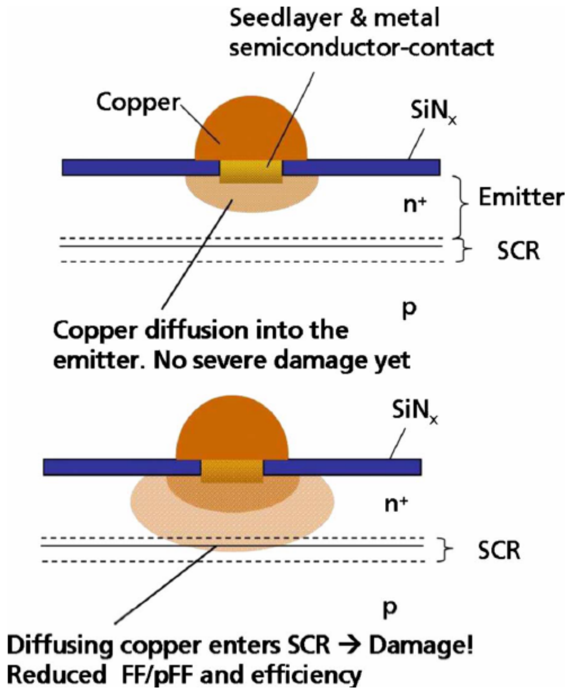


Fig. 6. Failure mechanism of copper diffusion in silicon solar cells. Reduction of FF/pFF and thus cell efficiency occur when copper enters the SCR[18)]

has been shown to result in high module efficiency, but subsequent thermal cycling and humid tests did not indicate copper diffusion to silicon. Other recent results also show a newly developed copper paste that provides similarly low contact resistance compared to silver paste and cured at low temperatures in a "standard" atmosphere after screen-printing. However, the line resistance was much higher than both the low-temperature paste and the high-temperature silver paste.

2.3 Loss characteristics of PV module

The loss of the solar cell module can divide into various failure factors because of the manufacturing process and the aging of the module as shown in Fig. 7[19)]. The types of loss in the manufacturing process are as follows; (1) the use of wrong output solar cells: In general, the several dozens of solar cells connect to the module. If a solar cell with an incorrect output is in use among dozens of solar cells, it will adversely affect the overall output of the module. It can improve the module lifetime by the selection of uneven wrong output solar cells. (2) Micro-crack of the solar cell during the manufacturing process: Tabbing & String process requires the heat and physical force, and micro-cracks may occur into the solar cell. As in the tabbing & string process, the crack can occur in the solar cell during the lamination process, which is also one of the leading causes of

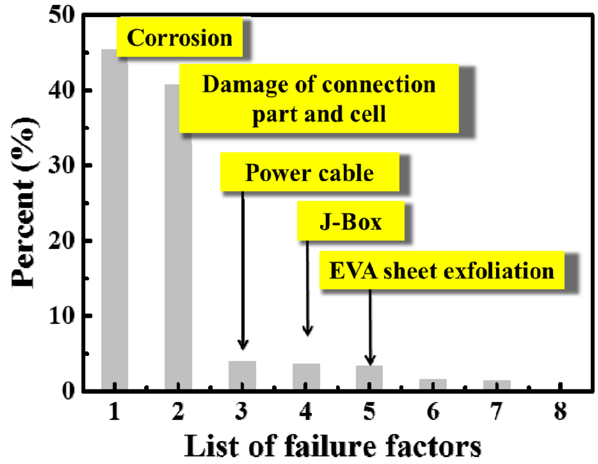


Fig. 7. An example of analysis of the degradation of PV module

degradation of module output. (3) Separation of module back sheet after lamination: lamination and curing process progressed, module connects to each layer and back sheet surrounding the back of partial module separated. It gave rise to a lack of adhesion during the lamination and curing process. The back sheet occurred the damage easily in the field, and it degraded the module output because of moisture ingress. (4) Bubbling after lamination: The bubbles generated in the lamination process reduce can act as a cause of reducing the output of the module. (5) Damage of back sheet during module installation: It causes scratches on the backside of solar cell module due to the mistake of the worker, which reduces the output of the module. (6) Module Delamination: We could observe the phenomenon that the layer of the module installed in the outside separates due to the lack of curing time or the defective EVA. This phenomenon accelerates the corrosion of the module electrode, which can cause the reduction of a power output. (7) Degradation of the module in the normal circumstance: EVA sheet discolors due to ultraviolet (UV) rays or heat, and the hazy color because of the air penetration between the glass and EVA sheet, resulting in a reduction of transmittance[20)]. (8) Pb (lead) contained in the ribbon that connects the solar cell. When this component penetrates the chlorine component in the atmosphere, $PbCl_2$ and $PbCl_2$ reacted with the air containing carbon dioxide and oxidized to $PbCO_3$. After that, an oxide layer formed on the surface of the ribbon, and the ribbon oxidized by repeating the above reaction. As of this phenomenon, corrosion occurs in solar cell modules. Fig. 4 shows the analysis of possible causes of aging of solar cell modules. The corrosion and breakage of solar cells or connection parts account for 85% of total degradation[21-27)].

3. Reliability improvement of PV module

It is necessary to judge whether it is suitable for long-term life through the test procedure required by crystalline silicon solar cell module. We called as IEC 60721-2-1, and the test procedure carried out to show long-time exposure under various environments. The concept of the reliability test which was different a lifetime warranty of more than 25 years[28]. Reliability test can perform a requested function under a given condition. This reliability included the elements and specific conditions and described in IEC 60050-191 as part of a whole concept of dependability.

Fig. 8 shows an example of three types of solar cell modules. In general, module failures fall into three categories: infant, midlife, and wear out failure. In addition to these, many PV modules show LID due to light immediately after installation[29]. Initially, quality and shipment inspection are considered normal, but they are stressed due to external factors (storage, logistics, installation and environmental conditions), resulting in defects. When accelerated under various conditions for the stress, it is certified through a standard test with an improvement of the cause.

Since the solar cell module requires a lifetime warranty of more than 25 years, various reliability tests are needed to reduce the failure rate even from the fundamental quality defect to the wear out failure region. In the reliability test, the lifetime of the product estimated through the accelerated life test. The life and the lifetime-stress relationship should set by evaluating the existence of the product under various conditions. The main factors of the accelerated life test affecting the performance or lifetime of the solar cell module are mechanical stress due to an ultraviolet ray of sunlight, temperature change, humidity, the wind, snow, ice, hail, and salt, other corrosive gas or sand, dust[30-32]. As the solar cell module exposed to the outside for a long time, the electrode oxidized due to various factors such as moisture, and the resistance is rapidly increased to decrease the efficiency. The reasons are as follows. The effectiveness of the solar cell module decreases when the resistance of the ribbon electrode itself and the series resistance of the connection portion between the electrode and the cell increase. Due to the influence of external temperature and humidity and the surrounding environment, the link between the solar cell surface electrode and the solar cell is oxidized to increase the deterioration of the electrode, and the series resistance of the solar cell is generated to reduce the voltage and current.

The silver or SnPbAg paste as the electrodes of the solar cell reasonably corrodes when exposed to moisture. Cracks and constant stress of the SnPbAg paste deteriorated at the contact portion between the electrode of the solar cell and the conductive ribbon. The contact resistance increased because of the destruction of the solar cell module, and the solar cell module cannot function as a solar cell module with time. If chlorine is present at the junction between the solar cells, the SnPb alloy reacts with them to form $PbCl_2$. $PbCl_2$ is not stable in humid air containing carbon dioxide and becomes porous $PbCO_3$, causing the corrosion. After that, an oxide layer formed again on the alloy surface of the SnPb, and the process mentioned above repeated until the entire SnPb alloy corrodes and disappears. To protect the solar cell module from these problems, the life of the solar cell module can prolong, and reliability can ensure by selecting a proper material and manufacturing the solar cell module according to sound characteristics of each material.

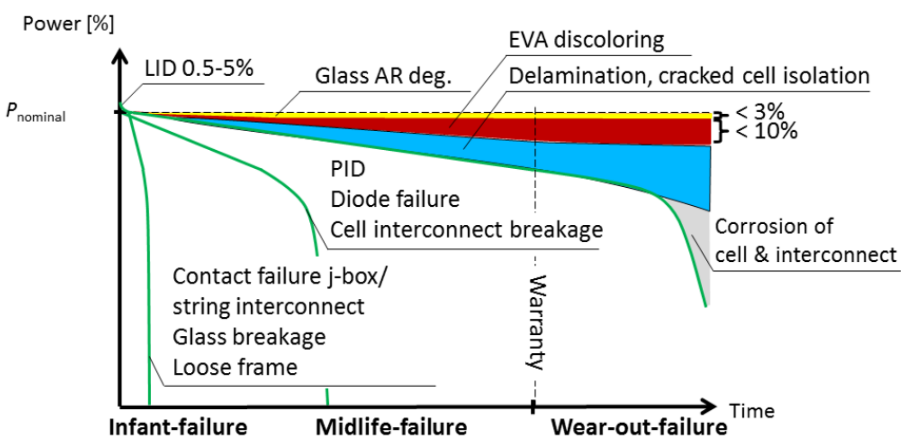


Fig. 8. Typical three failure scenarios of a wafer-based crystalline solar cell module

4. Way to improve the PV module performance, and conclusion

So far, we discussed the improvement of the module, the outline of the manufacturing method, loss characteristics and reliability according to the module construction material and failure mechanism. We also discussed the cause and solution of the power degradation in the present situation of the PV modules. It is necessary to develop technology for improvement of long-term reliability and to secure the competitiveness of photovoltaic energy.

We propose to improve the performance of the solar module, but we will focus on crystal silicon. (1) Cast crystal growth analysis and decision control, (2) Thin wafer slicing technology, carp reduction, and handling technology. (3) Ag replacement metal paste and specification technology, (4) Low-cost mass production process (cleaning, p-n formation, patterning, thin substrate) technology. (5) High throughput mass production, (6) Alternative substrate formation technology (epi growth technology for the base electrode substrate), and (7) uniformity doping techniques of n-type silicon crystal (reduction of resistivity distribution by ingot position). (8) Bulk lifetime enhancement technology by minimizing defects and impurities. In the future, if a high-efficiency solar cell using a thin wafer developed, it is necessary to solve the problems that may occur during the module manufacturing.

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