PV Module Degradation Mechanisms under Different Environmental Stress Factors

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Abstract

Understanding the degradation behaviours of photovoltaic (PV) devices is critical for optimising its financial viability. The degradation of PV modules is dependent on multiple factors such as installation site, mounting conditions, manufacturing process and module types. This means that in order to understand the long term behaviour of PV modules, one needs to assess the stresses acting on the modules (first two factors) and the module's response to these. In this paper, the possible degradation mechanisms within a PV module according to different stress factors are discussed and linked to typical module constructions. The relationships between degradation mechanisms and electrical performance are analysed as a first step to predict long term power degradation.

1. Introduction

Photovoltaic (PV) modules experience a complex set of environmental stresses during outdoor operation. These lead to overall performance losses affecting electrical and thus financial performance of the system. Accurate prediction of the power degradation is difficult as different stresses will trigger different degradation mechanisms at different rates. A number of degradation mechanisms have been observed and investigated [1, 2]. However, their dependence on operating conditions is not fully understood yet. To gain a better understanding of the ageing behaviours of PV modules, this paper will analyse different degradation mechanisms under different environmental stresses and link them with module structure and electrical parameters. This is the first step to understand PV module stability from integrated material, environmental and electrical perspectives. In the following, first the module structure and possible failure mechanism are reviewed. Then some specific degradation mechanisms are discussed and the clues given in the literature on how these affect device performance.

2. Degradation Mechanisms under Different Environmental Stress Factors

2.1 Typical structure configuration of PV modules

Of particular interest in this paper is the structural configuration of PV modules, as it reveals possible ways/areas of degradation. Normally, cell matrix is enclosed by polymeric pottant with both front and back structural support layer to protect them from outdoor stresses (Fig. 1) [3]. The top layer of the module is usually low-iron glass with good light transmission property. The commonly used materials for backsheet include polyvinyl fluoride (TPT), glass, anodized aluminum, and epoxy board. The pottant in solar modules are important material to provide structure support, mechanical protection, electrical isolation, optical coupling and thermal conduction. The dominant material for encapsulant is ethylene vinyl acetate (EVA), while other materials like polyvinyl butyral (PVB), and thermoplastic polyurethane (TPU) have also been used. Interfaces between different layers include glass/encapsulant, encapsulant/cells, encapsulant/backsheet are also critical as the heterogeneity of adhered materials can induce various degradation mechanisms.

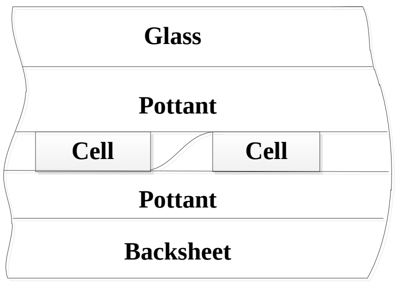

Fig. 1. Schematic cross-section of a PV module

2.2 Thermal induced degradation

The temperature of modules is usually higher than ambient temperature. Usually thermal effect acts as an accelerating factor for degradations caused by humidity or irradiance. However, thermal cycles can reduce module reliability in a number of ways (Fig. 2). For glass, residual strains may exist after lamination which can result breakage or delamination between glass/pottant under thermal strains. For encapsulant, different potothermal and thermal reactions can happen together with UV radiation from light. The principal reactions of

EVA are what called Norrish I and Norrish II (Fig. 3). In Norrish I, the vinyl acetate group can take off from the main chain to form acetaldehyde together with some gases which have potential to further lead to bubbles in the module. In Norrish II, C=C bonds (polyenes) are formed which have been widely considered as the chromophore group for EVA discoloration. Besides that, acetic acid is produced to catalyse discoloration and corrosion reaction. The polyenes produced in Norrish II can further be oxidised to form α-β unsaturated carbonyl, another product leading to discoloration. Besides chemical reactions, polymer may also undergo morphology changes under high temperature. Cells can also suffer from thermal fatigue with reported cracking and solder joint degradation. With regards to interfaces, the thermal heterogeneity of different materials can induce cracks, bubbles and delamination under daily thermal cycles.

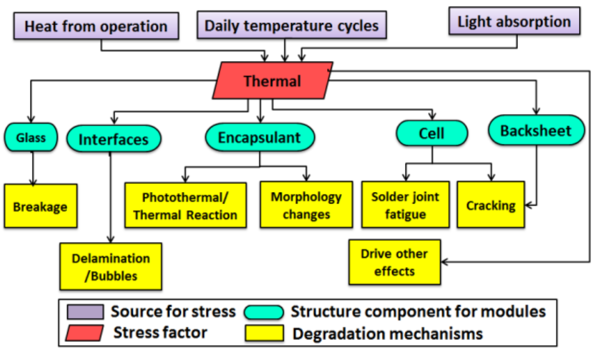

Fig. 2 Thermal-induced degradation

Besides these direct defects, temperature can accelerate many degradation processes. The water diffusion through polymers has been reported to be accelerated by temperature in the Arrhenius form [5]. Other procedures like metallisation corrosion, leakage current, diffusion of dopants, impurities etc., occur more rapidly at higher temperature.

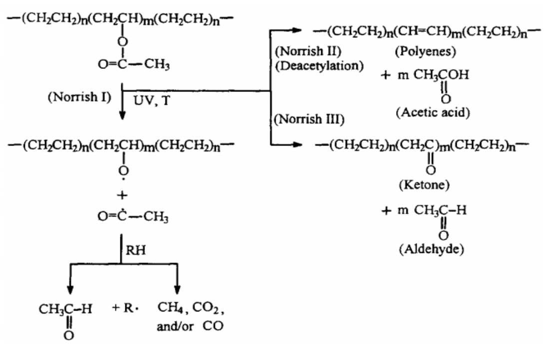

Fig. 3 Possible degradation mechanisms of EVA induced from UV and thermal stress [4]

2.3 Humidity induced degradation

Fig. 4 demonstrates humidity induced degradation on different components of PV modules. For glasses, increased conductivity is possible. For encapsulant, complex degradation mechanisms have been observed. From optical perspective, moisture may cause light transmission reduction. McIntosh [6] analysed the optical degradation of encapsulant under damp heat test condition of 85°C/85% RH. It was observed that moisture can reduce light transmission either by scattering the incident light or increasing light absorption coefficient of encapsulant. Another concern is copolymer hydrolysis result acidification and depolymerisation when hydrolytic bonds exit within backbone. Dielectric property may also change with decreased insulation characteristics. The main concern about cell degradation under humidity is corrosion which can occur at cell grid lines, bus bars, interconnects and lead. Ionic materials can be ionized in water to form electrolyte where the electrochemical corrosion occurs. Backsheet, under humid environment, is possible areas for moisture ingress. Many degradation mechanisms have also been reported in interfaces. First, delamination can occur as a result of ice expansion or the hydrolysis of siloxane bonds between the silane coupling agents in encapsulant and glass. The delamination will alternatively enhance water ingress and cause ensued problems like decoupling of light transmission and reduction of heat dissipation. Increased conductivity is another issue by shunting current out of the system through these interfaces [7].

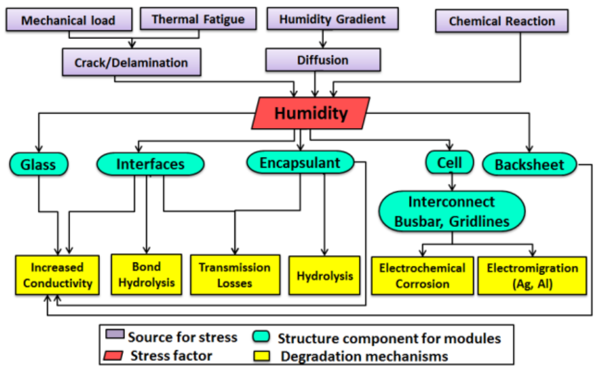

Fig.4. Moisture induced degradation

2.4 Irradiance induced degradation

Possible degradation mechanisms under irradiance are presented in Fig.5. Light induced degradation (LID) is one of the main ageing mechanisms. Boron-doped Czochralski-grown silicon (Cz-Si) solar cell with high O_2 concentration is known to suffer from efficiency degradation. This phenomenon is first observed by Fischer and Pschunder in 1973 [8]. There are no comprehensive explanations to this defect yet, but one model that is widely accepted is created by Schmidt et al [9] to attribute the lifetime degradation to an interstitial boron-oxygen pair acting as recombination center that are created under illumination and dissociate at temperatures above 200°C. The LID is also observed in a-Si solar cells called the Staebler-Wronski effect (S-W-Effect) which was first described by Staebler and Wronski in 1977 [10]. They discovered a reversible photoelectronic effect that the photoconductivity and dark conductivity of a-Si will decrease under illumination and will completely recover by annealing above 150°C. Reflecting to performance, it is a large power degradation of 10% to 30% within the first few months of operation. The mechanisms for the carrier lifetime degradation/recovery cycles for a-Si are still unclear now but many different models have been established attempting to give a reasonable explanation, such as breaking of weak Si-Si bonds by nonradiative recombination producing defect centers that lower carrier lifetime, the capture of carriers at existing charged dangling bond sites etc. [11].

Except semiconductor, encapsulant is another vulnerable component under irradiance. In fact, UV light is the primary stressful factor for polymers as its high energy content. Photons in irradiance can activate polymer elements or their additives to create free radicals, the initials for oxidation and other reactions. One example is EVA degradation together with the effects of heat as shown in Fig. 4. It is the main reason for EVA discoloration.

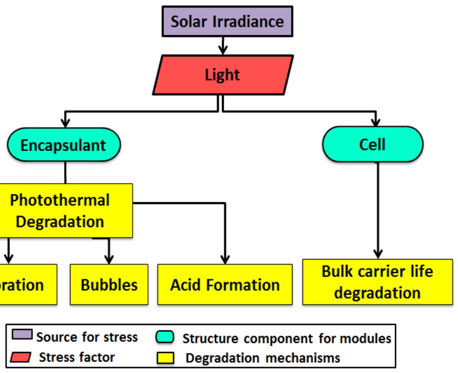

Fig. 5 Irradiance-induced degradation

3. Interrelationship between Degradation Mechanisms, Module Structure and Electrical Circuits

In this section, the single diode model of PV modules is used as a medium to link material degradation with module electrical deterioration. The influences on electrical properties are expressed by the changes of parameters of light-generated current (Isc), series resistance (Rs) and parallel resistance (Rp).

3.1 Performance Degradation caused by PV module encapsulant

Fig. 6 is an example of how encapsulant material degradation influences electrical performance of PV modules.

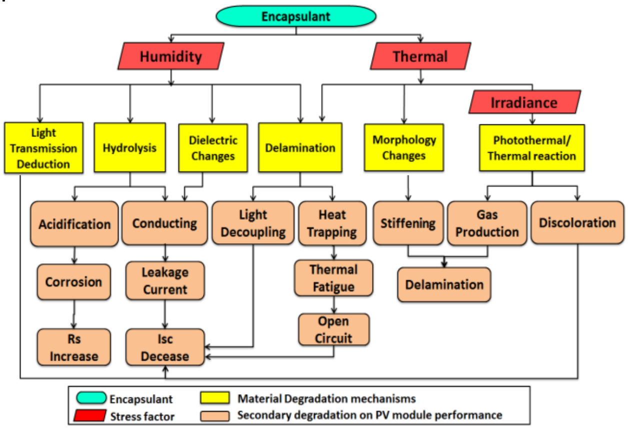

Fig.6 Degradation mechanisms of PV module encapsulant and the influences on module performance.

The light transmission deduction of PV encapsulant caused by moisture will reduce the amount of light absorbed by the semiconductor and thus caused decreased photocurrent (Isc). Copolymer hydrolysis will produce acid groups to catalyse metallisation corrosion and at the same time supply electrolyte and thus lead to increased Rs. However, besides water and electrolyte, oxygen is needed for corrosion to happen. Therefore, the extent of corrosion is suspect. The hydrolysis will increase polymer conductivity and cause leakage current. The leakage of current is actually a reduction of the current received by the load whose effect is equivalent to Isc reduction. Dielectric property changes of the polymer can also deteriorate its insulation resistance with a potential for leakage current and thus a reduction of Isc. Delamination between encapsulant and substrate or cells can cause severe performance degradations. Delamination can result decoupling of light transmission reducing the effective number of photons received by the cell with a potential to reduce Isc. It can also weaken and even interrupt heat dissipation within the module to cause hot spot and thermal fatigue and even open circuit to reduce the power output. Under thermal fatigue, polymer recrystallization can occur leading to stiffening of the polymer and thus delamination. Discoloration of EVA as the result of phothermal and thermal reaction can reduce Isc. However, some outdoor exposure indicated that the effects on Isc are not significant [12]. Meanwhile, the gases produced during this process can cause bubbles and accelerate delamination to degrade module performance. However, to what extent of these material degradations is needed for these effects to be observable is not known.

3.2 Degradation mechanisms grouped by single-diode model

Table 1 summaries how the material changes of other components of the PV modules influence power output.

Table 1 Degradation grouped by different categories

Degradation Categories	Degradation Behaviours	Influenced Materials	Contributing Stress
Isc Losses	Light scatting by water	Interfaces and bulk encapsulant	Moisture, Temperature may drive moisture ingress
	Increased light absorption	Pottant	Moisture, thermal
	Encapsulant Discoloration	Pottant	Irradiance, Thermal
	Light transmission decoupling due to cracks, delamiantions and bubbles	Glass, cell, interfaces	Thermal fatigue, Moisture
	Light induced degradation	Cell	Irradiance
	Diffusion of dopants/impurities causing recombination	Cell	Voltage, Thermal
R_S Increase	Front/back contact/ Interconnect/lead corrosion	Metal components	Moisture, voltage, temperature may accelerate
	Solder joint crack	Solder Joint	Thermal
	Metal Electro migration/Diffusion	Metal component	Voltage, temperature may accelerate
	Diffusion of dopants lead to bulk Si resistance increasing	Semiconductor	Voltage , thermal
R_{sh} Reduction	Leakage current	Interface, pottant, glass surface	Voltage, Moisture
	Encapsulant dielectric damage	Encapsulant	Moisture
	Cell junction conductivity increase	Semiconductor	Voltage

4. Conclusion

PV module degradation mechanisms under typical environmental stress factors have been detailed. A network regarding to PV module degradation has been established linking ageing mechanisms with module material and electrical parameter changes. Comprehensive research about degradation under different stress factors on material and device level as well as on controlled and field-aged modules are needed for the prediction of module degradation rates.

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