Definition, Classification and Inspection Methods of Cracks in Photovoltaic Cell -- Cracks Induced by Vibration Caused by Transportation

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This paper discusses cracks in photovoltaic cell caused by en-route transportation to customer, often discovered by observing power efficiency reduction in final photovoltaic cell and module products, or outright disruption of electrical generation for that particular solar cell. The vibration by different transportation modes might induce crack propagation. Crack propagation of inner micro-cracks might lead to larger cracks in the millimeter or larger scale. These larger cracks affect the solar cell product quality. How to define these cracks and classify them pertaining to which ones might be contributing to potential power efficiency reduction is very important for the ability to define higher quality and yield photovoltaic cell products. Furthermore, crack observation and inspection methods in the manufacturing lines, field implementation, and during en-route transportation to customer site, and crack observation after installation were discussed and addressed. Cell vibration test methods will be addressed in a separate paper.

Introduction

Photovoltaic cells and modules are usually transported by land, sea and air freight before they reach customer sites. Occasionally, customers observed power efficiency reduction of final photovoltaic cell products or outright disruption of electrical generation. Tests were done before product ship-out and after receiving at customer sites. There exists differences in data and this issue might be cause for argument. It was found that shipping damage is always one of the top photovoltaic failure issues in the field. This calls for detailed research in this industry-wide study by the SEMI International Standard Program, Taiwan Photovoltaic Technical Committee, Photovoltaic Cell Vibration Task Force.

This task force set up a series of experiments in order to understand the effect of vibration caused by transportation on photovoltaic cell reliability. The vibration parameters are based on ASTM and MIL-STD standards to simulate different modes of transportation (land, air and sea). After vibration test, we analyze the solar cells by different methods used in solar factories. The first method is electrical analysis, to identify damaged vs. non-damaged photovoltaic cells, by simply measuring their electrical performance, per IEC standard. The result shows 5 percent of all photovoltaic cells with abnormal efficiency compared to other cells, and less than one percent of cell breakage. However, electrical analysis can only detect cells which have already shown their abnormal (or broken) status, but still cannot detect those cells which show normal efficiency at that moment, but are already or potentially broken. We have then seen micro-cracks, which could not be detected initially, appearing on the cell. These micro-cracks might eventually lead to bigger cracks later, induced by vibration due to transportation. The electrical efficiency is hence reduced. For this reason, we need to find an appropriate inspection tool to detect micro-cracks. Then we can find the "broken cell suspects," to enhance and ensure the reliability of final solar cell products.

Typical inspection tools providing relatively good capability of detecting cracks and available on the market are as follows: Electroluminescence (EL) [1], Photoluminescence (PL) [2], Near infrared camera (NIR) [3], Resonance ultrasonic vibration (RUV) [4], Scanning acoustic microscope (SAM) [5] and RHT[6、7]. These tools are usually aided by visual inspection and microscopes. For this experiment, we use an inspection method consisting of electroluminescence and optical microscope. It provides a good speed and high magnification to find defects on the photovoltaic cells.

With the support of industry, we have abundant sources of photovoltaic cells and professional vibration know-how. The result of the experiment is very interesting. 6 obviously broken cells were observed as the result of the vibration. On these broken cells, we detect many micro-cracks by using portable digital microscope(s). Similar cracks are potential starting points leading to broken solar cells. We also started with a draft concept of classification preliminarily. On the other hand, we find out the portable digital microscope acts as important role by providing sufficient magnification of details and its convenience. We believe that it will be important amongst the inspection systems aiding the solar production lines in the future.

Description of the Overall Vibration Experiment

In order to understand the phenomenon of photovoltaic cell under vibration during transportation, this task force designed a vibration experiment to simulate the real situation. As industry usually transports photovoltaic cell by air and land, these two transportation modes are targeted in our experiment. The parameters are set up according to ASTM, MIL-STD standards, and the detail numbers will be discussed in another related paper.

After experiment setup, we start to standardize how to package photovoltaic cells. The way we package them is elaborated as follows: As shown in Figure 2, we put multiple photovoltaic cells and stack them as a block, multiple blocks are stacked as a box, and we ship layers of boxes together in a unit, or normally called a pallet. For example, in our experiment, there are four layers in this unit, each with six boxes. Every box contains 10 blocks, and each block has 100 pieces of photovoltaic cells. As a result, there are totally 24,000 cells vibrating simultaneously at every vibration experiment. As it is unnecessarily, time-consuming, and cost-prohibitive to have 24,000 cells for each experiment, we selectively choose positions of measurement, and select the test blocks of known good cells that shall undergo the pre-test and post-test examinations to determine the distribution of defects after the vibration response.

We selectively place accelerometers in key measurement locations according to possible vibration modes in each of the boxes. The configuration of accelerometer position is explained as the right diagram of Figure 2. There are four main accelerometers (labeled with red color) installed in each layer, because these accelerometers are enough to show the whole vibration phenomenon, considering the symmetry in geometry. We also put another accelerometer (labeled with green color) for reference, confirming whether the vibration phenomenon is symmetric.

Figure 1 Vibration Experiment - Shaker.

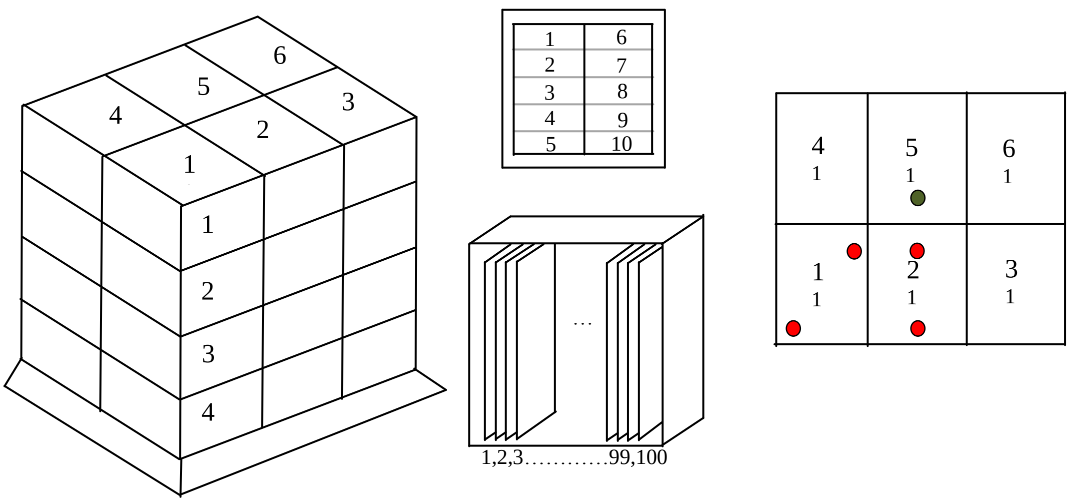

Figure 2 Vibration Experiment Setup and Configuration

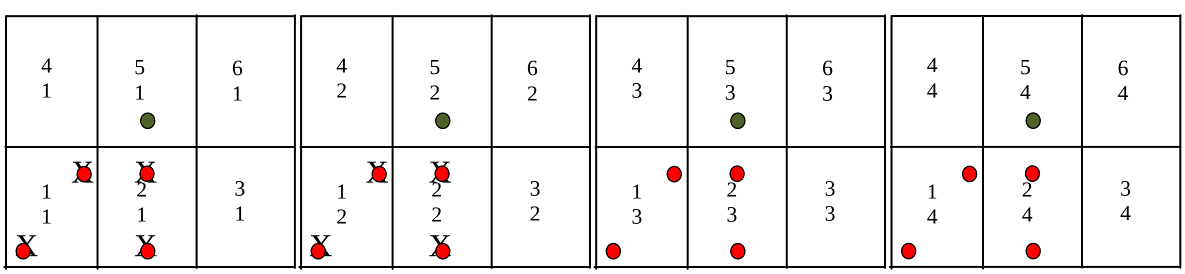

Figure 3 Positions Showing Maximum Vibration Response.

We then use electrical analysis to test photovoltaic cells to find the ones which are already showing bad performance, according to the IEC standards. Then the electroluminescence and portable digital microscopes are used to find the possible suspects for broken photovoltaic cells.

Vibration, Cracks and Micro-Cracks

Vibration Analysis

The purpose of vibration test is for us to understand first the cell breakage rate caused by vibration. We also want to use spectrum analysis to study more about the vibration phenomenon, and to find the potential relationship between cell reliability and vibration caused by transportation.

The concept is that we can find the natural frequency of photovoltaic cells, and then the appropriate package will be designed in order to lower frequency response to a low-enough standard level not to have negative influence on the photovoltaic cells.

The natural frequency of photovoltaic cells is measured to be around 29 Hz, and whole package's natural frequency is about 7 to 10 Hz., and maximum response is on the upper layer of the whole package, as shown in Figure 3. All of these result and more detailed content of vibration analysis are discussed in another related paper. We are using this result to help our understanding of the following related research.

Electrical Analysis

During analysis of electrical parameters, we decide to measure several parameters of photovoltaic cells: efficiency, fill factor, shunt resistance, series resistance and power maximum point. They are measured at the time before and after every vibration test. The result of the analysis shows that there is apparent increase of abnormal photovoltaic cells after the vibration. Broken photovoltaic cells are at about 1%, and abnormal photovoltaic cells are about 5%. More detailed content of electrical analysis is discussed at another related paper.

Crack, and Micro-cracks - Post Test Examination

There can be inherent defects and dislocations existing in the poly-silicon photovoltaic raw wafer material. Cracks and defects on the photovoltaic cells induced after vibration test exist in many forms and sizes, from micron-scale micro-cracks to millimeter or centimeter cracks. On the other hand, these cracks under effect of external excitation or vibration by different transportation modes might also cause crack propagation – because crack propagation of inner micro-cracks might lead to connection of smaller defects or micro-cracks into larger cracks in the millimeter or larger scale. [8] These larger cracks affect the solar cell product quality. Crack propagation would lead to reduced efficiency or even outright cell breakage. The existence of these induced cracks is shown to have reduced electrical efficiency, as measured by max power drop in the vibration experiment. Therefore, how to detect these cracks accurately become very important if more reliable, higher-yield and better quality photovoltaic cells are desired.

For the industry, finding photovoltaic cells which have already shown abnormal performances or breakage is not enough. We hope to find all the "broken cell suspects." According to previous research papers, lots of inspection methods have been studied thoroughly, but there still are not much research about the causes, definition and classification of the cracks appearing on the photovoltaic cells. However, knowledge of causes, definition and classification play an important role on judging whether the photovoltaic cell is "broken cell suspects." Therefore, we decide to start research of this field, and the inspection tool set we chose is electroluminescence and optical microscope.

Microscopic Picture Analysis

Photovoltaic cells are made with polycrystalline material structure, and therefore we can see lots of grain boundary in Figure 4 (a) and (b) - taken by the portable digital microscope - MGP4-Plus (30X, White light lens with 470nm filter). With this setup, the grain boundary features on the photovoltaic cells are enhanced. These grain boundaries are potential sites to produce cracks when the external stress and excitation are applied.

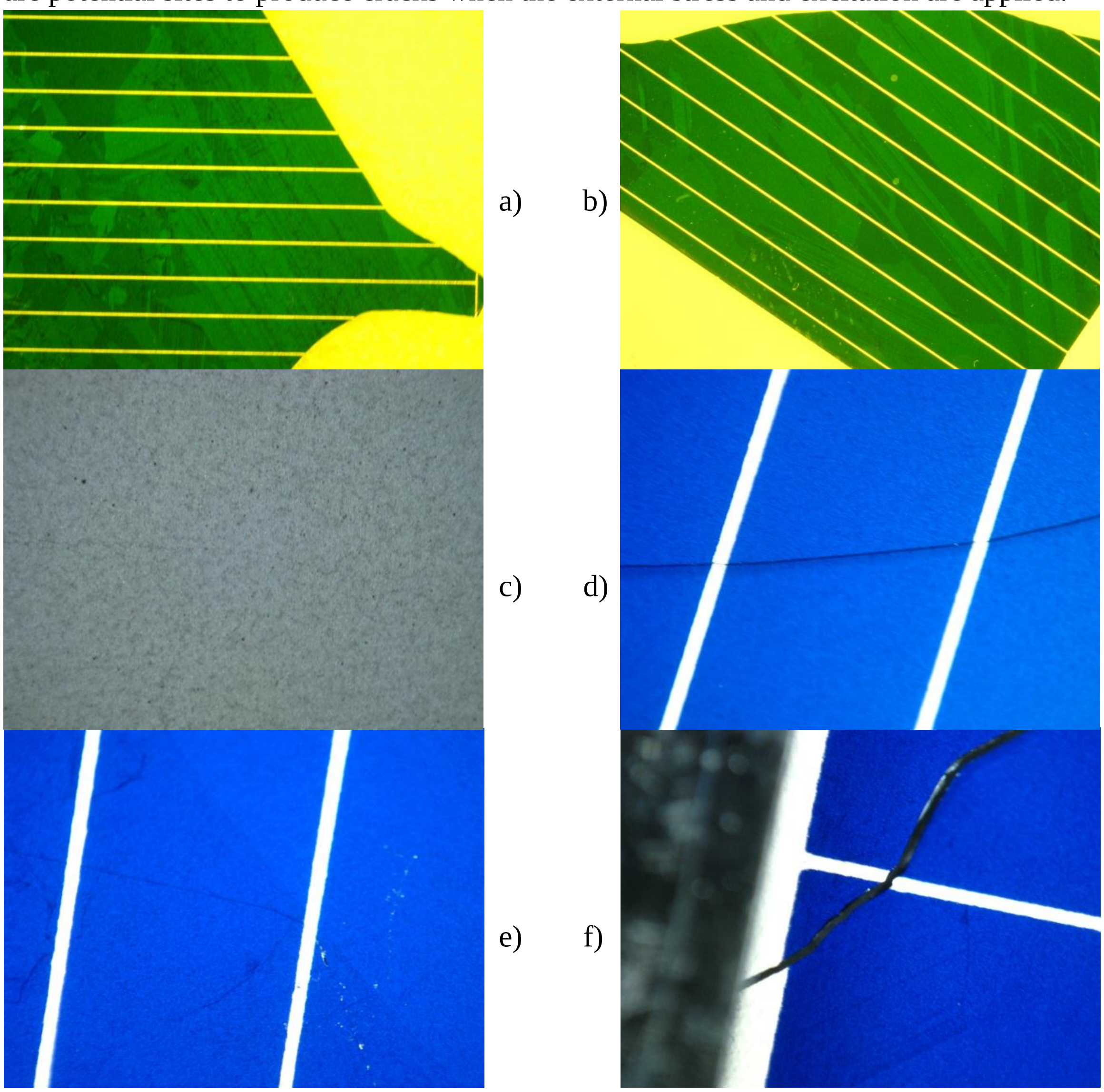

Figure 4 Microscopic Pictures of Cracks and Micro-cracks.

These photos can be used to determine and verify whether later-on vibration-induced cracks might be grain-boundary, dislocation related, or simply vibration or shock induced. These photos are also taken during post-test examination to confirm the result.

At higher magnification, taken by the portable digital microscope – G20 (60X, 150X, and 300X White light lens), we find there are many cracks and micro-cracks in the photovoltaic cells, during post-test examination. Micro-crack is defined here as non-visible cracks below ~30-50μm. G20 at 300X magnification has detection resolution limit of crack below 1.5um wide. Figure 4 (c) is an example of photovoltaic cell starting to show hair-line crack that extends across the cell, where the crack tip is shown on this photograph. Initially, these hairline cracks are very hard to see, as their width might only be as thin as several microns wide extending several mm to cm long. Observation from the backside of the photovoltaic cells sometimes would help locate these hairline cracks better than on the front-side of the cell, as shown in Figure 4 (d), a more developed and more visible single crack of at least 5 mm long and tens of micron wide. In Figure 4 (e), we can see cracks are extended out with multiple side-cracks of length around 50-600μm and about 10 μm wide. These cracks might develop into large cracks leading to cell breakage, shown in Figure 4 (f).

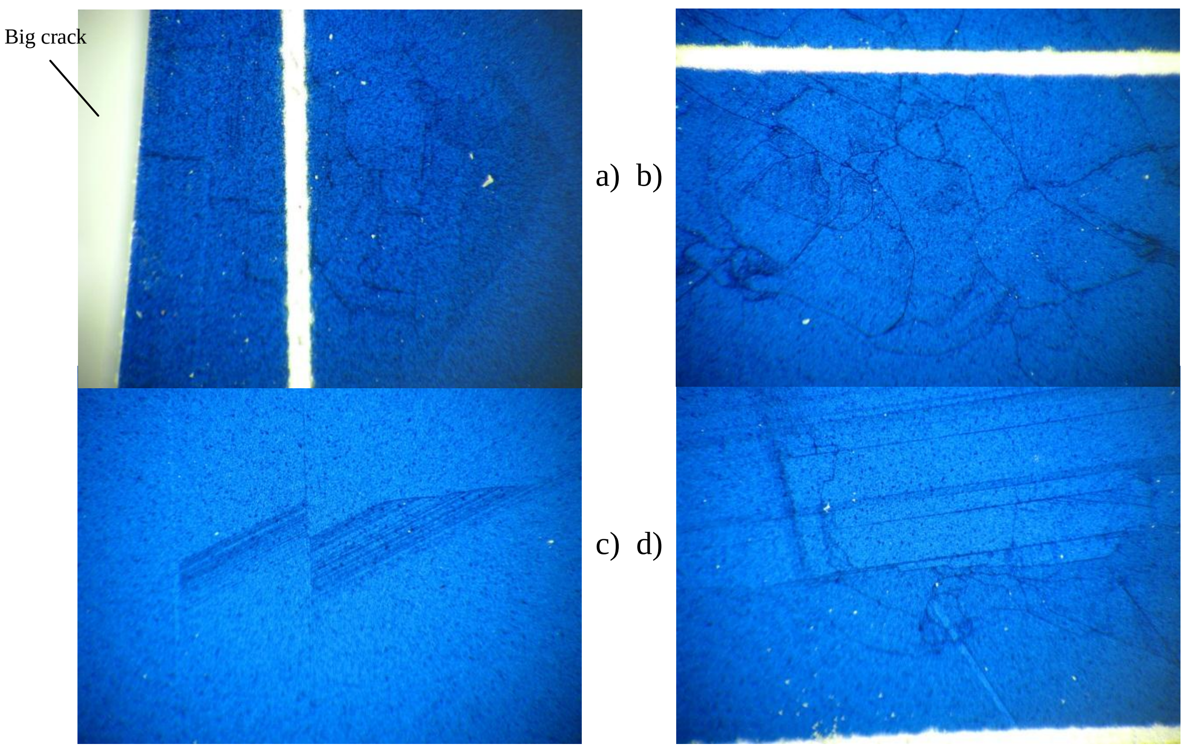

Figure 5 Microscopic Pictures of Micro-cracks and Other Defects.

After the vibration experiment, we looked at the broken cells in detail. We can see the micro-cracks extending out from the major crack/breakage in Figure 5 (a). The finding of these micro-cracks is important, because they might be sites where, after external excitation and stress, it might lead to big crack or even cell breakage, big enough to have negative impact on cell performance and reliability, according to previous paper [8]. Figure 5 (b) shows a very clear picture of vibration-resulted cracks and micro-cracks of sized between 20-1000μm long and several-teens of μm wide. These cracks were not there before the vibration. Figure 5 (c) is a clear image to see scratches on photovoltaic cells. These scratches might be caused by friction between cells, usual hand-handling of 2 or more cells, mechanical-handling by automation, or by worker's mindless touch. We are not sure whether these scratches could be causes for further crack development. But in Figure 5 (d), we can also see scratches and micro-cracks co-exist in the same photograph, therefore we caution that these scratches might potentially have some contribution to micro-cracks, if cells are mishandled. Figure 5 (a), (b), and (d) were previously not noticed in production lines.

Crack Definition and Classification

Through above-mentioned experiment result, we can see many different cracks. These cracks and defects appearing on the photovoltaic cells can be in many forms and sizes, from micron-scale micro-cracks to millimeter or centimeter cracks. How to define these cracks and classify them is very important for the ability to define better quality and higher yield photovoltaic cell products.

The physical phenomenon of crack development, the most straightforward and helpful method to determine whether the micro-crack has any effect on cell performance, is the concept that we consider to classify these cracks or micro-cracks. For example, if one of the micro-cracks is caused by impact during vibration, a major damaging phenomenon, then we can use "impact-induced crack" to describe this micro-crack. There are different kinds of stress caused by vibration, especially from vertical load caused by Z-axis vibration, which might cause edge chips and cracks. There are also some cracks created alongside grain boundaries. Even the friction caused by sliding between cells would some extent influence the photovoltaic cell performance. However, as other physical phenomenon might be very complex, it is still very hard to specify every micro-crack with the real physical phenomenon which produces it. We would need to do many elaborate experiments, very detailed analysis, using professional knowledge of material to verify the phenomenon and to complete the classification task.

Therefore, we think that in order to define a crack or micro-crack, one must first describe by

(1) its length and width; a non-visible crack of < ~30-50μm is called micro-cracks.
(2) single simple crack, branch, multiple branches, tree-like cracks, web-like cracks, shatter-like cracks, etc.;
(3) point defect, fissure, line cracks, angled cracks, zig-zag cracks, curved cracks, etc.

Based on typical industry quality control specification, we progress further with a draft classification, as follows: Table I is the classification of different photovoltaic cells and Table II is the classification of defects.

TABLE I. Classification of Photovoltaic Cells - Typical Industry Defect Definition.

No.	Defect Name	Description	Accept/Reject Criteria
1	Broken cells	Cells with broken areas.	Reject if broken into pieces.
2	Cracked cells	Cell with visible cracks.	Reject for any visible cracks or micro-cracks. Wafer/cell with visible cracks.
3	Chips/Divots	Cells with chips.	Reject if chip/divot area >= Xmm2 or quantity >1. Reject in any case if chip touches the grid line.
4	Holes	Holes in cells.	Reject for any visible holes in silicon.
5	Bow	Bow in cells	Reject if cell bow is >Ymm measured from flat surface

TABLE II. Classification of Defects of Photovoltaic Cells - Typical Quality Control Specification.

No.	Item	Specification	Classification
1	Break	Unacceptable	Major
2	Crack	Unacceptable	Major
3	Chip	Length≦X mm, Depth≦Y mm, ≦Z per wafer; V-shape chip unacceptable	Major
4	Crystallinity	Multi-crystalline	Major
5	Micro-grain	【1】Grain ≥ nXn mm² 【2】If grain < nXn mm²，Area ≤ n²cm²	Major
6	Scratch	Free	Minor
7	Surface quality	As cut, cleaned contamination free	Minor
8	Saw mark	≦XXμm	Minor

Crack Propagation

According to Sadananda, et. al. [9], a crack or micro-crack will remain dormant when the threshold stress is not reached. For a given material, the modified Kitagawa diagram in fatigue (Figure 6), defines the conditions under which a crack initiated at the threshold stress becomes a propagating crack, by satisfying the threshold stress intensity. Internal stress or local stress concentration are required to provide the necessary mechanical crack tip driving forces to have the initiation and propagation of the cracks. The processes underlying the crack nucleation and the crack growth of a material require building up of internal stresses by local plasticity. The process involves crack tip blunting and micro-crack nucleation until the crack becomes unstable under the applied stress.

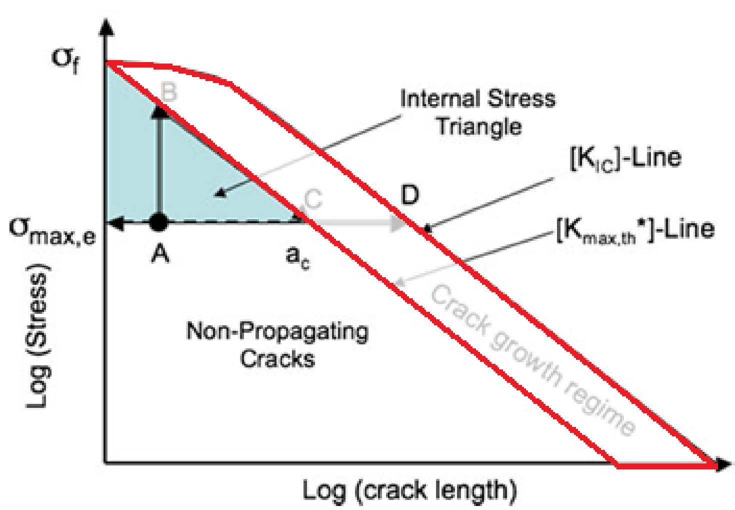

Figure 6 Modified Kitagawa Diagram for Fatigue – Describing the Point at Which a Crack Becomes a Propagating Crack.

Inspection Methods of Cracks and Micro-Cracks

As the reference literatures indicated in the Introduction section, there are many existing researches on inspection methods of photovoltaic cells. However, every inspection method has its advantage and disadvantage. Typical inspection tools providing relatively good capability of detecting cracks and available on the market are as follows: electroluminescence, photoluminescence, near infrared camera, resonance ultrasonic vibration, scanning acoustic microscope and RHT. These tools are usually aided by visual inspection and microscopes.

Among these methods, electroluminescence and photoluminescence use external bias to make solar cell emit infrared light due to band-to-band electron hole recombination. CCD (Charged-coupled diode) camera then is used to detect the infrared signal emitted by cells. These two methods exhibit advantages of (1) non-destructive nature and (2) fast detection rate of potential defects. However, they still have the following disadvantages:

* Having difficulty of clearly determining the existence of cracks, or small-and-narrow cracks with length less than ~ 1 cm.
* Not capable of finding micro-crack, and
* Sometimes, the existence of defects causes reduced minority carrier lifetime, so it would not emit enough infrared signal to effectively detect the defects.

The principle of NIR detection is by using scattering of the near infrared light at the micro-crack planes that transmits through the wafer and reflected at the internal surfaces due to the micro-cracks inside the wafer. It exhibits speed of inspection and the ability to find cracks inside the wafer. Nevertheless, NIR camera fails to detect cracks on cells which are processed with aluminum coating material on the backside of wafer blocking the near-infrared light; therefore, the ability to detect cracks disappears thereafter.

RUV is an effective method to detect cracks in solar cell for its high-speed and accuracy. It basically emits ultrasonic wave toward cells, and judges cells' quality from their frequency response. However, RUV also has the problem that it cannot acquire defect image if researcher needs to do some research about the cracks.

The last two methods, SAM and RHT, also have very good ability to find cracks; however, they take long time to completely analyze each solar cell, around 10-15 minutes.

<u>Inspection Tool Unit (Electroluminescence + Optical microscope)</u>

For this experiment, we choose an inspection method combining the convenience of electroluminescence (EL) and optical microscopy (OM) into a tool set, because they are readily available in the factory floor and can provide both the speed (by electroluminescence) and the high magnification in finding defects on the photovoltaic cells (by OM). We use electroluminescence to detect possible defects up to millimeter scale, and then to use OM to confirm possibly defects with its high magnification, down to low single-digit micron-scale, a low-enough scale where even-smaller defects might not affect the reliability of the solar cell. By doing so, we can detect and confirm the "broken cell suspects" with great details, without spending too much money. However, the non-mobility of the OM makes this inspection method not able to be implemented across solar production lines, with the same reference method from wafer to cells and finally to module production lines. Hence, we introduce the portable digital microscope to resolve this problem, and it does prove that it can acquire comparable magnification with its mobility, and consistency throughout wafer, cell, and module production lines.

Both electroluminescence and portable digital microscope are non-destructive in nature. Electroluminescence has now been commonly used in the photovoltaic industry. The principle is to induce infrared light of photovoltaic cell itself by external bias voltage, then use near infrared camera to record the image and detects the defect. The advantage of electroluminescence is its high-speed, which can meet the standard of industry requirement, but the disadvantage is its inability of detecting detailed condition of photovoltaic cell. For example, it cannot distinguish the difference between scratch and crack of photovoltaic cell. In Figure 7, we can see some defects in the electroluminescence photographs but are not quite sure whether the defects or possible cracks appearing on the photovoltaic cell are truly cracks. In this case, portable digital microscope is handy in providing further details with more thorough inspection.

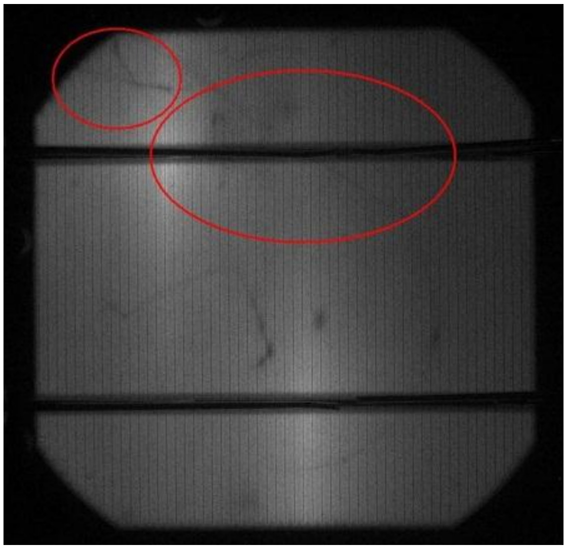

Figure 7 Electroluminescence Picture of Cracks.

Portable Digital Microscope

Limited by optical micro-scope's non-mobility, this inspection method cannot be uniformly implemented across solar production lines. For example, normal optical microscope can only be applied at fixed locations on cell production lines, but cannot be used for module production lines due to its limited mobility.

To resolve this problem, we introduce the portable digital microscope (Figure 8), which is one type of optical microscope. The main feature is that it provides mobility while also with good magnification (300X). At this magnification, portable digital microscope has the ability of telling the difference between scratch and crack, also meeting our requirement to detect micro-cracks below 30-50μm with good mobility. Actually, the minimum-size crack on photovoltaic cells we can see is down to ~1.5μm in width. These micro-cracks are very likely to be the factor leading to cell breakage, especially when micro-cracks can propagate into larger cracks under stress. In addition, we can easily apply many light sources (UV light, Infrared light, and visible light) on portable digital microscope units.

As a result, portable digital microscope does prove that it can acquire high magnification microscopic pictures with its mobility. It can also serve as a consistent and convenient crack observation and inspection tool set throughout wafer, cell, and module production lines - for the manufacturing lines, field implementation, and during en-route transportation to customer site, and crack observation after installation. This is a good tool to assist the existing EL and PL methods used in current photovoltaic cell factories.

We think that even smaller magnification in the range of 0.1~5μm range can also be studied using much more expensive scanning electron microscope, but its destructive nature, requiring cells to be broken while preparing the samples (hence this method cannot preserve the micro-cracks on cells), would not serve the purpose of observation. Also, observation down to 2-3μm scale using portable digital microscope already provides more than enough details of the defects, where more details are not necessarily gaining benefit, and the cost of using the expensive scanning electron microscope is not necessary.

Figure 8 Portable Digital Microscope for Detecting Cracks and Micro-cracks.

Conclusions and Future Work

In this paper, we have addressed the experiment system, crack observation, definition, classification, and inspection method for cracks and micro-cracks induced by vibration caused by transportation. The result of the extensive vibration experiment shows that even with a very effective package, transportation-induced vibration can cause less than one percent of cell breakage, and 5 percent of photovoltaic cells with abnormal efficiency compared to normal cells. Cell breakage mostly depends on the stresses induced in the processing, handling and transportation, and the presence of defects such as micro-cracks.

The study also shows that our attempt to define and classify the cracks proves to be hard at this point, and much more efforts will be needed to continue this study. However, we have good progress in crack observation and inspection methods in the manufacturing lines, field implementation, and during en-route transportation to customer site, and crack observation after installation. We find that combining electroluminescence and portable digital microscope is a convenient tool set to detect cracks. This inspection tool set provides good speed from electroluminescence with good detail information from portable digital microscope's magnification. We now have a tool to easily detect micro-cracks below 30-50μm, and believe that these micro-cracks might potentially be the reason leading to bigger crack (millimeter level) or even breakage. Also, portable digital microscope let this inspection tool set able to be applied across solar production lines with its mobility. Therefore, it has been shown to be a very useful tool alongside other main production inspection tools mentioned above to clearly define the existence of cracks or micro-cracks, with clarity and details previously not shown in existing production environment. We believe this tool set will be very promising for inspection system of photovoltaic production lines, with more work to be done for further improvement in the future, such as better crack definition and classification methods.

After this experiment, we understood the root causes leading to micro-cracks are very complex, and more experiment and analysis need to be done to be able to make good classification. We will work on inspection system integration and further research of micro-crack classification in the future.

Acknowledgments

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