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Reliability evaluation of III-V Concentrator solar cells

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ABSTRACT: Concentrator solar cells have been proposed as an interesting way of reducing the cost of photovoltaic electricity. However, in order to compete with conventional solar modules it is necessary not only to reduce costs but also to evaluate and increase the present reliability. Concentrator solar cells work at higher temperature, solar radiation and current stress than conventional solar cells and a carefully reliability analysis is needed. In this paper a reliability analysis procedure, that is being developed, is presented.

1 INTRODUCTION

The rate at which the photovoltaic industry expands is exponential, with a constant and quick renovation of both technology and materials. To guarantee the credibility of this growing industry, a reliability testing plan is needed, IEC 61215 (2005), which is usually known as Highly Accelerated Lifetime Testing (HALT), Ton et al. (2007). Nowadays, this plan is partially developed for silicon solar modules, but in the case of concentration systems this plan has to start from scratch.

Since the very early stages of photovoltaic research, the use of concentrated light has been considered as an interesting way of reducing the cost of photovoltaic electricity. In recent years, there has been a significant advance in the field of III-V high-concentration solar cells, achieving efficiencies of 26.2% at 1000 suns, Algora et al. (2001).

Conventional silicon solar modules have very high reliability, with warranties higher than 25 years. If III-V high-concentration solar cells based systems are expected to compete with the existing silicon technology, they must reach similar values of warranty. Therefore, before reaching the industrialization stage, it is necessary to demonstrate the long-term behavior of these devices. For doing so, we have defined a working plan for assessing the reliability of these new devices, which can be seen in Figure 1. The main reasons of the need of this plan are:

1. There are no previous studies of these devices that evaluate the main reliability parameters, such as Mean Time To Failure MTTF, failure rate ($\lambda(t)$) or reliability function ($R(t)$).
2. It is not possible to test the device under real working conditions in climatic chambers. Therefore, it is necessary to simulate electrical and thermal real conditions, and to incorporate the acceleration factors, González et al. (2006).
3. As a result of the previous condition, it is necessary to develop models that from the dark I-V curve, recorded while the experiment is ongoing, allow the evaluation of the power loss by the devices in the test.
4. Failure mechanisms and how they affect the device performance are completely unknown. A comparison analysis with high power Light Emitting Diodes (LEDs), which are very similar devices in terms of materials and manufacturing technology, can help to develop a strategy to evaluate the device reliability, analyzed by Vázquez et al. (2007).
5. To establish a correlation between Highly Accelerated Life Test (HALT) results of reliability and

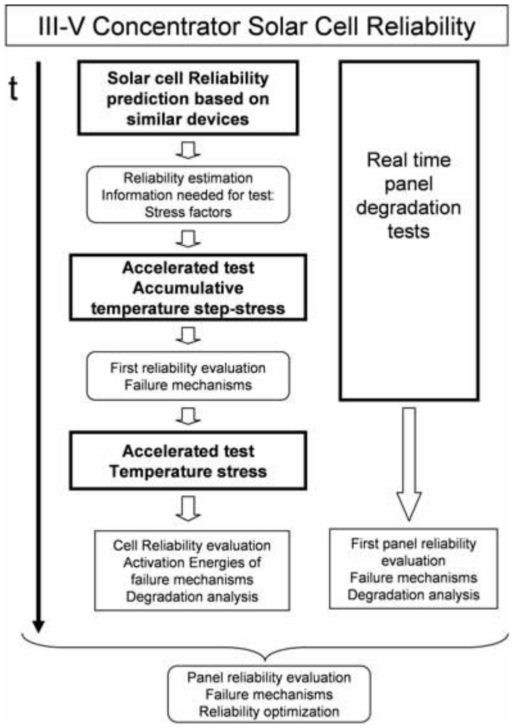

Figure 1. III-V Concentrator solar cell reliability activities.

failure mechanisms and the results of reliability and failure in field observations.

In this paper a reliability analysis procedure and preliminary results are presented. This procedure consists on the following activities:

1. ***A prediction reliability analysis based on similar devices.*** The first activity that must be carried out according to this plan is the analysis of the possibility of achieving at least values of reliability similar to conventional silicon solar modules. III-V high concentration solar cells are based on a technology similar to LEDs. A detailed analysis of the factors that affect their reliability such as temperature, current and humidity has already been done by Vázquez et al. (2007).
2. ***Accelerated tests.*** The reliability of these devices is expected to be very high, of the order of millions of hours. In order to obtain reliability data in a suitable period of time HALT are needed. Some of the tests of the working plan have already been done and the rest are ongoing.
3. ***Real time degradation tests.*** To study the degradation of the whole device in real operating conditions as well as the degradation of the optics and the panel, a two-axis sun tracker has been installed. The I-V curves in darkness and illumination are being recorded to follow the evolution of the performance of each cell.

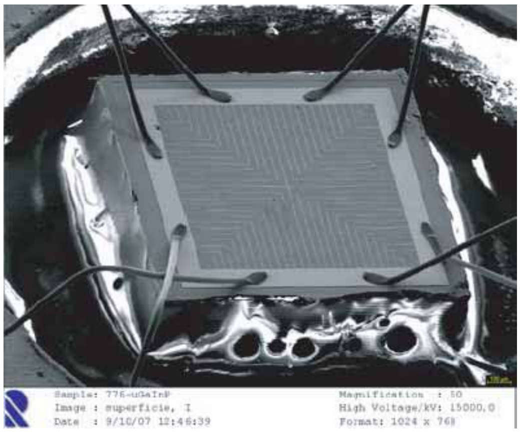

Figure 2. Imm^2 solar cell.

In the following these activities will be described deeply.

2 SOLAR CELL DESCRIPTION

The III-V high concentrator solar cells used in this work were manufactured on semiconductor structures grown in a metal-organic vapor phase epitaxy (MOVPE) reactor. The devices were fully processed in the *Instituto de Energía Solar* laboratory using optoelectronic techniques to get small area solar cells (1 mm^2), see Figure 2. A full description of the semiconductor structure and the manufacturing process can be found elsewhere by Rey-Stolle et al. (2000).

Each individual solar cell works at 1000 suns receiving a luminous power density of 1MW/m^2, which means a harsh working environment.

3 III-V CONCENTRATOR SOLAR CELL PREDICTION

III-V high concentrator solar cells based on Light Emitting Diode (LED) technology have been proposed and developed in recent years as a way of producing cost-competitive photovoltaic electricity. As LEDs are similar to solar cells in terms of material, size and power, it is possible to take advantage of the huge technological experience accumulated in the former and apply it to the latter. Another important subject, is that the luminous power that LEDs can supply has risen dramatically in recent years with the development of high power LEDs. This kind of devices require higher current stresses and therefore reliability will be affected to a higher degree.

3.1 *III-V solar cell versus high power LED*

As was mentioned in the introduction, one of the possibilities for reducing the cost of III-V high-concentration solar cells is to implement a manufacturing technology similar to that used for LEDs (Light Emitting Diodes). This is commonly known as the "LED-like approach" by Algora et al. (2005). From this premise, the similarities between both types of devices will be shown in the following paragraphs, as well as the main factors that affect LED reliability. Some of the similarities see by Algora (2006) are related to materials, size, heat removal and manufacturing process.

In order to analyze how to extrapolate LED reliability experience to III-V high-concentration solar cells, it is necessary to find out the role played by the semiconductor material and the working conditions in the device reliability, analyzed by Narendran et al. (2004), and the LED white paper of Hewlett Packard and Marktech Optoelectronics. The main variables that affect to the reliability are the semiconductor material, the temperature, the current stress and the humidity. This factor are analyzed with some detail in the following.

- ***Material.*** III-V high concentrator solar cells are based on AlGaInP semiconductor family, which is the same that red, orange and yellow LEDs use. Nowadays, AlGaInP compounds are a mature technology with defects densities as low as 10^2-10^3 defects/cm^2. Operational lifetime of AlGaInP LEDs exceeds 10^5 hours. This value will be taken into account as a reference for the reliability prediction in these solar cells.
- ***Temperature.*** Regarding the working temperature, III-V high-concentration solar cells have some advantages with respect to high-power LEDs as:
  - ***Less heat to be dissipated.*** A III-V high-concentration solar cell working at 1000 suns receives a luminous power density of 1 MW/m^2. Therefore, for a chip size of 1 mm^2 the luminous power received is 1 W. Considering an efficiency of 30%, 300 mW are converter into electricity and 700 mW are transformed into heat that must be evacuated. This power is lower than high-power LEDs with the same chip size that must evacuate about 850 mW[4].
  - ***More room to dissipate heat.*** LEDs are usually encapsulated in small packages allowing little room for heat sinks. On the other hand, III-V high-concentration solar cells could have more room to dissipate heat, depending on the particular design of the panel.
- ***Current density.*** Typical current density values of high-power LEDs are between 50 to 100 A/cm^2[2], while typical current densities for high-concentration III-V solar cells are in the range of 15 A/cm^2, when operating at 1000 suns (measured under AM1.5D low AOD -Aerosol Optical Depth-spectrum). In other words, LEDs current densities are roughly a factor of 3 to 6 higher than current densities of III-V MJ solar cells working at 1000 suns. Besides, the current density differences are not only in magnitude but also in terms of current distribution.
- ***Humidity.*** III-V high-concentration solar cells, in the same way as LEDs, must be protected from the harsh effect of humidity and thus they need complete sealing packaging.
- ***Photodegradation.*** In contrast to high-power LEDs, in solar cells, not only the encapsulant but the semiconductor die is affected by photodegradation. III-V high-concentration solar cells are placed inside an optical system which concentrates up to 1000 times the light of the sun where both the encapsulant and semiconductor is affected by the solar radiation.

Based on the AlGaInP operational lifetime and analyzing the similarities between III-V solar cells and high-power LEDs, it is possible to take advantage of the accumulated experience in LED reliability and apply it to solar cells. From a detailed analysis it can be seen that the main factors related to high power LEDs reliability are less stressed in solar cells. As a result, we can conclude that high concentrator III-V solar cells would be able to achieve operational lifetimes similar to AlGainP LEDs (100,000 hours). Assuming that solar cells only work on average 8 hours per day, 100,000 hours will correspond to more than 34 years of real-time operation.

4 ACCELERATED TESTS

Accelerated reliability tests are used to evaluate the device reliability in a suitable period of time. In this first attempt, single junction GaAs high concentratior solar cells were used. The working conditions were simulated by forward biasing the solar cells at the same current level (250 mA, i.e. 25 A/cm2, for these GaAs based solar cells) that they would handle at the operating concentration (i.e. 1000 suns).

The test circuits have six bare cell mounted in alumina substrate, in order to increase the dissipation capacity (Fig. 3). Two type of solar cell technologies A and B, have been used in the accelerating test. Twelve cells of type A (A1 to A12) and eighteen cells of type B (B1 to B18) have been tested at the same time.

Figure 3. Bare solar cells soldered in alumina substrates.

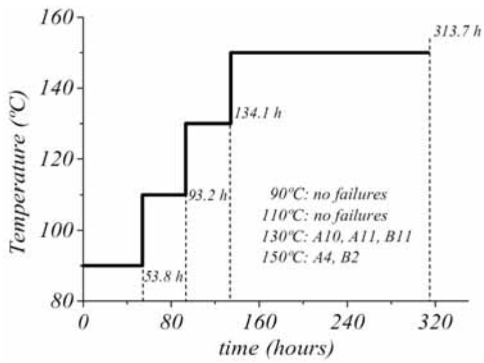

Figure 4. Temperature step stress test.

The evolution of devices under test was monitored recording the dark I-V curve at regular time intervals during the test. Even though the best choice for monitoring the performance of the solar cells is to record the illumination I-V curve, this can not be done easily inside a climatic chamber keeping standard conditions in all measurements.

Two accelerated test are being carried out with III-V high concentrator solar cells:

- ***Temperature step-stress*** has been carried out with the same solar cells at four different temperatures: 90°C, 110°C, 130°C and 150°C (Fig. 4). There were not failures in the 90°C and 110°C steps, but there were three failures in the 130°C step, (cells A10, A11 and B11) and two failures in the 150°C step, A4 and B2. This type of test is more difficult to analyze because of the cumulative stress that devices suffer along the test, but with it, is possible to obtain much more information in one go. A deeper analysis of the obtained data is ongoing and preliminary results show that:
    - From these acceleratedtests it can be observed that solar cells are very robust devices and the type of failure is not affected by temperature in this range.
    - Only gradual failures, not catastrophic, have been observed.
    - For all the cells that presented failure ($\Delta P > 10\%$ at 1000 suns), there was an important degradation in the open circuit voltage (V_{oc}), which is one of the parameters that describes the performance of a solar cell.
    - Finally, a surprising result has been found in the evolution of the short circuit current (Isc). Even though it was assumed to remain constant, an increase of this magnitude has been observed in all devices.
- ***Conventional temperature accelerated stress:*** in order to get the main reliability functions, as well as the energy activation we are carrying out this test. It will be done on independent groups of samples at two different temperatures. Reliability results at working temperature will be extrapolated by means of the Arrhenius equation. These experiments are on going and we expect to have preliminary results in short.

5 REAL TIME DEGRADATION TEST

A two-axis sun tracker has been installed at the flat roof of the IES-UPM to study the global device degradation in real operating conditions, as well as the degradation of the optics and the panel, see Figure 5. The I-V curves in darkness and illumination are being recorded to follow the evolution of the performance of each cell. With every measurement the meteorological and irradiation data are also collected, in order to get normalized results. The modules' assembling allows independent access to every solar cell (i.e. an ad hoc connection scheme has been implemented).

Figure 5. Two axis sun-tracker high concentrator solar module.

The analysis of the collected data is ongoing and first results will be available soon.

6 CONCLUSIONS

In this paper we have proposed a procedure to evaluate the reliability of III-V high concentrator solar cells. The reliability evaluation in a short period of time has difficulties because it is not possible to measure the solar cell performance inside a climatic chamber. This reliability procedure consists in three different activities:

- ***Reliability prediction*** based on similarities with High Power LED. These results show that high concentrator solar cells could achieve reliability higher than 10^5 hours, that corresponds to 34 years assuming 8 hours of daily operation.
- Two different ***accelerated tests*** have been proposed. Temperature step stress has been carried out, with temperatures ranging from 90°C to 150°C. The results show that failure mechanisms are probably due to a degradation in the V_{oc} and do not change in this temperature range. Conventional temperature accelerated tests are on going in order to evaluate the reliability at working conditions.
- ***Real time degradation time*** is being developed and preliminary results will be available in short.

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