STATISTICAL CALCULATION OF THE MAIN RELIABILITY FUNCTIONS OF GaAs CONCENTRATOR SOLAR CELLS

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ABSTRACT

This paper presents some of the results of a method to determine the main reliability functions of concentrator solar cells. High concentrator GaAs single junction solar cells have been tested in an Accelerated Life Test. The method can be directly applied to multi-junction solar cells. The main conclusions of this test carried out show that these solar cells are robust devices with a very low probability of failure caused by degradation during their operation life (more than 30 years). The evaluation of the probability operation function (i.e. the reliability function R(t)) is obtained for two nominal operation conditions of these cells, namely simulated concentration ratios of 700 and 1050 suns. Preliminary determination of the Mean Time to Failure indicates a value much higher than the intended operation life time of the concentrator cells.

INTRODUCTION

In recent years, significant advances have been made in the field of concentrator III-V multijunction solar cells (MJSCs), achieving peak efficiencies of 32.6% at 1000 suns for a dual junction solar cell [1] and 43.5% at more than 400 suns for a triple junction solar cell [2]. In spite of these good results, concentrator III-V MJSCs are still at an early stage of commercial deployment and there are many open issues about their reliability.

The most spread PV systems are those based on conventional silicon flat modules. These are reliable systems that have been deployed in field applications for more than 30 years. Nowadays, silicon manufacturers' warranties usually extend to 25 years of use, and are expected to increase to 30 years in the near future [3]. If CPV systems are going to compete with silicon flat modules, they must be covered by similar extended warranties. However, the reliability of these devices must be first confirmed, before such extended warranties may be issued.

Even though a standard for qualifying CPV modules and assemblies was issued some years ago [4], there is a lack of normative for qualifying concentrator III-V MJSCs. Besides, it must be kept in mind that reliability is a completely different issue. Reliability tests should be directed not only to determine how long devices are going to live, but also the influence of the operating conditions. In other words, reliability is also interesting in knowing the probability distribution of failure in nominal conditions of operation.

Consequently, reliability statistical methods must be applied to III-V MJSCs with the aim of determining the main reliability functions. In view of the similarities between some type of III-V concentrator solar cells and *light emitting diodes* (LEDs), the life time of CPV solar cells was predicted to be characterized by, at least, a *Mean Time To Failure* (*MTTF*) of up to 10^5 hours [5] (equivalent to 34 years assuming an average of 8 hours of operation per day). This *MTTF* value prediction was updated by a step-stress accelerated ageing test, in which a functional *MTTF* of 69 years was calculated with a 90% unilateral confidence interval [6]. The failure analysis showed that the uncoated solar cells failed because of perimeter shunting.

With the aim of increasing the accuracy of the main reliability functions determination, this work presents a completely new set of tests which have been carried out over GaAs single junction solar cells. From these tests, some novel results (such as the determination of the activation energy associated to the degradation mechanism) are presented in this paper. Once all the procedures, equipments, etc. had been proved with GaAs single junction solar cells and the determination of results had been successful, we will start the work for the reliability determination of MJSCs.

WORKING PLAN

We have defined a working plan to carry out the reliability assessment of concentrator solar cells. This plan consists of the following steps:

- Study of the solar cell from the design stage in order to assess the suitability of the materials used and the optimum configuration of the CPV system.
- Accelerated ageing tests, in order to shorten the time to evaluate the reliability. We have carried out two type of tests whose methodologies are described in detail in [7]:
  - Stage 1. Highly Accelerated Life Test (HALT), that consisted of a temperature step-stress test . The primary purpose of HALT tests is not to measure but to improve reliability. HALT tests are used in the early design and development phases to reveal potential failure modes.
  - Stage 2. Accelerated Life Test (ALT), which yields quantitative information that is more reliable than that gleaned from the highly accelerated life test (HALT) method. These tests are designed to

estimate product reliability. Some of which results are shown here.

- Real time tests. In order to determine if the stress factor introduces failures that would never happen in real operation.

The first set of reliability studies have been conducted on bare concentrator GaAs solar cells, but their reliability when operating inside a CPV module has not yet been determined. Therefore, we have also focused our testing working plan on assessing the reliability of the module, not only to gain insight into this point, but also to determine the real time evolution of the device. Accordingly, we have developed a statistical model for assessing the reliability of a photovoltaic module based on degradation data. The aforementioned model has been applied to an ad hoc manufactured CPV module, in which independent electrical access was provided to each receiver in order to evaluate the performance over time without the masking effects that a series or parallel connection configuration within the module may introduce [8]. Finally, our working plan includes accelerated ageing tests for triple junction solar cells based on laser illumination [9].

EXPERIMENTAL

The test carried out in [6] revealed some technological situations that were responsible for the solar cell failure. Small size high concentrator solar cells (about 1 mm^2) present a high perimeter/area ratio. It is well known that one of the most important defects that can be found in a crystal is the free surface, because of dangling bonds and crystal lattice interruption at surface. For this reason, the exposed perimeter is an ideal place for a chemical reaction with environmental agents to be enhanced because of a high current flow as well as a priority place for defects to migrate. One of the objectives of the new tests is to overcome this situation.

The assembly of the cells used in this test features the following characteristics (see Figure 1):

1) Encapsulation on Direct Bonded Copper (DBC) substrates to increase the thermal dissipation.
2) Encapsulated cells were attached to an aluminum box with a thermal-conductive adhesive.
3) Cells were covered with silicone, to simulate the real situation of a cell inside a secondary optics in a concentrator, which in addition protects the cells, in particular their perimeter.

A full description of the setup can be found in [10]. Working conditions were emulated [11] by forward biasing the solar cells at the same current level they would handle at two concentrations: 700 and 1050 suns. The tests have been carried out at three different high temperatures 130ºC, 150ºC and 170ºC.

Special care should be taken to the following aspects when dealing with temperature accelerated ageing tests:

- The test must be carried out at three different temperatures to determine if the acceleration factor of the degradation mechanism is according to the Arrhenius law.
- Both the temperature of the climatic chamber and the junction temperature must be accurately measured. For doing so, the junction temperature has been carefully controlled following a method described in [10, 12].

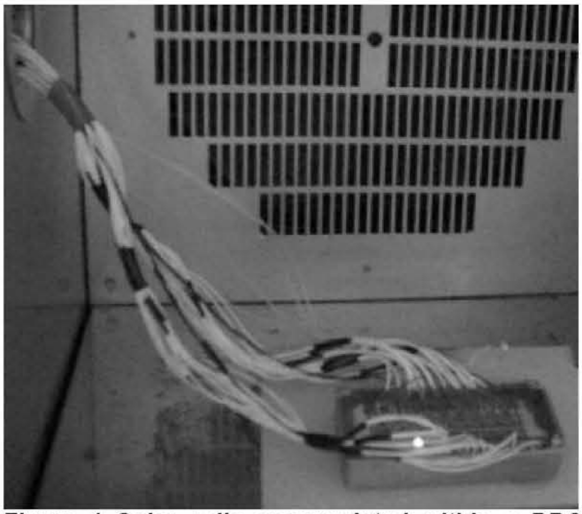

Figure 1 Solar cells encapsulated within a DBC substrate and covered with silicone inside an aluminum box in the climatic chamber.

RESULTS

A key consideration in reliability measurements is the definition of a suitable failure criteria. Two possibilities may be proposed:

- Catastrophic failure: the sudden breakdown of a solar cell, which results in an abrupt loss of power.
- Degradation failure: a gradual decrease in the cell power. Failure for the CPV system yielded a power loss of more than 20% compared with the initial performance. This power loss is typical of silicon flat modules [13]. We define a concentrator solar cell's failure as a power loss of 2.5%. This is because other elements of the CPV system can contribute to the whole power loss until a 20% decrease is observed. We consider this failure criterion for concentrator cells to be conservative.

		Average relative power loss		
T (°C)	Duration (h)	0X	700X	1050X
130	4232	0.24	1.69	-
150	5612	0.68	2.78	5.87
170	1026	0.55	2.57	-

Table 1 Average relative power loss for each test.

The experimental results show that no catastrophic failures were found in the solar cells tested at the three temperatures and at the two emulated concentrations. In other words, only degradation failure occurred. The results of the average relative power loss in each test are presented in Table 1.

Figure 2 shows the power evolution with time at 150ºC with a current injection equivalent to 700 and 1050 suns, respectively. These graphs show that after 5500 hours the power degradation is lower than 3% in the 700X case and lower than 6% in the 1050X one. In both cases there were two parts clearly different: an initial period in which the degradation rate is higher and a second one in which the rate slows down and tends to stabilize.

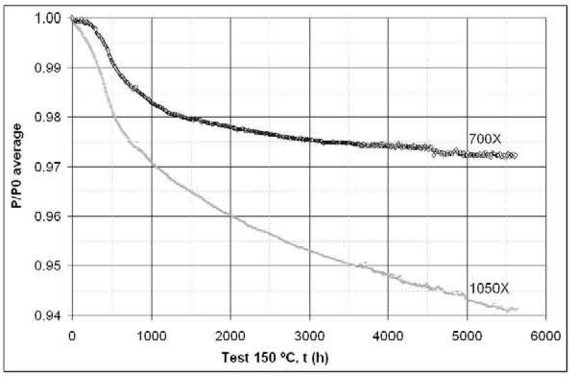

Figure 2 Experimental power evolution at 150ºC for two different evaluated concentration ratios.

The activation energy can be obtained from the Arrhenius life-stress representation (see Figure 3), resulting 1.02 eV. The good fits of the three average relative power curves over the duration of the long lifetime accelerated tests justify the use of the acceleration time factors of the Arrhenius law (Figure 4). To the best of our knowledge this is the first time this energy has been calculated for III-V concentrator solar cells. With this activation energy, the calculation of the acceleration factor can be carried out and the evolution of the relative power can be extrapolated to any working temperature.

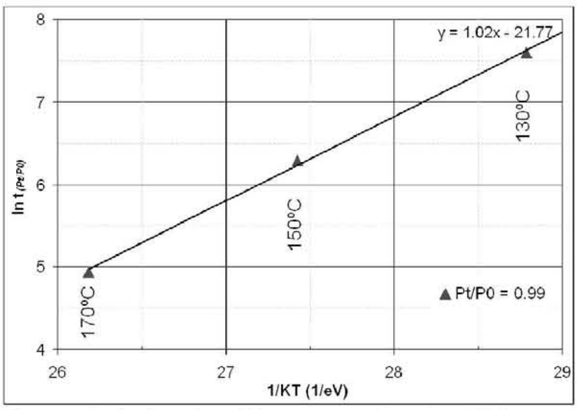

Figure 3 Arrhenius life-stress plot for 700 suns cells, for a degradation of 1% under three different temperatures of test.

Once the influence of the temperature in the degradation and reliability function has been determined by means of the Arrhenius law, the degradation and reliability at the cells working conditions can be calculated. Even though the tests are still on-going, the preliminary results show that the MTTF of the solar cells is at least one order of magnitude higher than previous test.

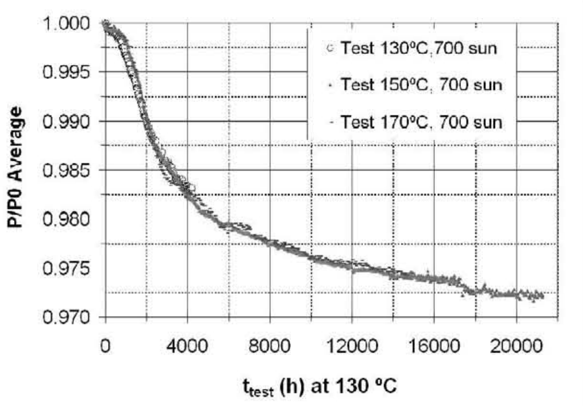

Figure 4 Measured average relative power curves at 700X. In the 150ºC and 170ºC curves the times of measured average relative power have been extrapolated at the time for T_{use}=30ºC.

Figure 5 shows the time-dependent reliability function at the cells' working temperature (65 ºC) for the two concentration ratios evaluated in this test, which is basically calculated by means of the model described in [13] for a 2.5% failure level (*FL* = 0.975) and using the aforementioned activation energy. From this plot, it is clear that the concentration has a strong influence in the shape of this function.

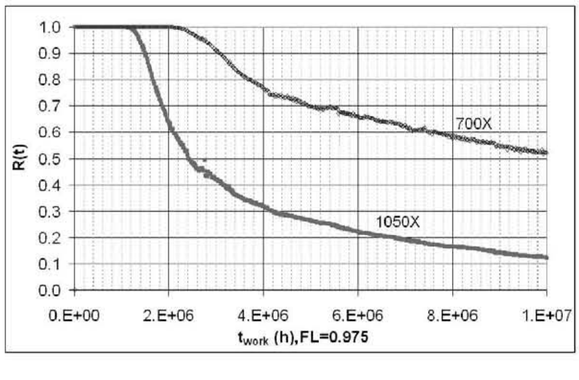

Figure 5 Reliability function at the working temperature (65ºC) assuming a failure limit (*FL*) of 2.5%.

SUMMARY AND CONCLUSIONS

This paper presents an accelerated life thermal test which has been carried out over GaAs single junction solar cells for simplicity but whose protocols and procedures can be directly extended to MJSCs. The main conclusions are:

1) No catastrophic failures have been observed. This indicates that the solar cells are quite robust at the typical working currents.
2) The degradation trend is the same for the groups of cells tested at different temperatures.
3) The degradation of the solar cells follows different trends depending on the current injection (concentration level).
4) A 2.5% solar cell power loss was defined as the failure limit *(FL)*. At this limit, the other elements of the CPV system contributed to the remaining power loss up to a 20% failure limit for the system. A value of 2.5% is considered to be conservative.
5) For the first time, the activation energy associated to the degradation mechanism has been calculated for this kind of devices, with a value of 1.02±0.04 eV.
6) With this value the reliability function has been extrapolated to the working temperature (65ºC).

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REFERENCES

[1] M. A. Green, K. Emery, Y. Hishikawa and W. Warta, Solar cell efficiency tables (version 36), *Prog. Photovolt: Res. Appl*. 18, 2010, pp. 346–352.

[2] http://www.compoundsemiconductor.net/csc/news-details.php?cat=news&id=19733359

[3] J. H. Wohlgemuth, Cunningham DW, Nguyen AM, Miller J., "Long term reliability of PV module." 20th European Photovoltaic Solar Energy Conference, Barcelona, Spain, 2005; 1942–1946.

[4] IEC62108: "Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval", Ed.1.

[5] M. Vázquez, C. Algora, I. Rey-Stolle and J.R. González, "III–V concentrator solar cell reliability prediction based on quantitative LED reliability data" *Progress in Photovoltaics: Res Appl* 15 (6), 2007.

[6] J. R. González, M. Vázquez, N. Núñez, C. Algora, I. Rey-Stolle and B. Galiana, "Reliability Analysis of Temperature Step-stress Tests on III-V High Concentrator Solar Cells". *Microelectronics Reliability* 49, 2009, pp. 673-680.

[7] Guangbin Yang, Life Cycle Reliability Engineering. Chapter 7. John Wiley & Sons, Inc 2007.

[8] J. R. González, M. Vázquez, C. Algora and N. Núñez, "Real-time reliability test for a CPV module based on a power degradation model", *Prog. Photovolt: Res. Appl*. 19, 2011, pp 113–122

[9] C. Algora, Reliability of III–V concentrator solar cells, *Microelectronics Reliability* 50, 2010, pp. 1193–1198.

[10] N. Núñez, M. Vázquez, J. R. González, F. J. Jiménez and J. Bautista, "Instrumentation for accelerated life tests of concentrator solar cells". *Review of Scientific Instruments*, 82 (2), 2011, 024703-024709.

[11] N. Núñez, M. Vázquez, J.R. González, C. Algora and P. Espinet "Novel accelerated testing method for III–V concentrator solar cells" *Microelectronics Reliability* 50, 2010, 1880-1883.

[12] P R N Childs, J R Greenwood and C A Long, Review of temperature measurement, Rev. Sci. Instrum. 71, 2000, 2959–78

[13] M. Vázquez and I. Rey Stolle. "Photovoltaic Module Reliability Model Based on Field Degradation Studies" *Prog. Photovolt: Res. Appl*. 16, 2008,: pp. 419–433.