Evaluation of the Reliability of Commercial Concentrator Triple-Junction Solar Cells by Means of Accelerated Life Tests (ALT)

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Abstract: A temperature accelerated life test on commercial concentrator lattice-matched GaInP/GaInAs/Ge triple-junction solar cells has been carried out. The solar cells have been tested at three different temperatures: 119, 126 and 164 ºC and the nominal photo-current condition (820 X) has been emulated by injecting current in darkness. All the solar cells have presented catastrophic failures. The failure distributions at the three tested temperatures have been fitted to an Arrhenius-Weibull model. An Arrhenius activation energy of 1.58 eV was determined from the fit. The main reliability functions and parameters (reliability function, instantaneous failure rate, mean time to failure, warranty time) of these solar cells at the nominal working temperature (80 ºC) have been obtained. The warranty time obtained for a failure population of 5 % has been 69 years. Thus, a long-term warranty could be offered for these particular solar cells working at 820 X, 8 hours per day at 80 ºC.

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INTRODUCTION

In the last years the efficiency of multijunction solar cells has increased considerably, with a current record efficiency of 44% [1]. Nevertheless, the Concentration Photovoltaics (CPV) community is aware of the fact that together with the efficiency increase, high reliability is essential in reducing the cost of solar electricity by extending system lifetime [2].

Current silicon modules are reliable systems which perform very well in the field with less than 1 % power loss/yr for more than 20 years [3]. If CPV wants to compete with silicon flat plate, similar or higher warranties are need. However, the knowledge of the reliability of concentrator solar cells is still scarce. Accordingly, the aim of this work is to present the main reliability functions and parameters of commercial lattice matched concentrator GaInP/Ga(In)As/Ge triple-junction solar cells obtained by means of a temperature accelerated life test.

ACCELERATED LIFE TEST APPROACH

The purpose of accelerated life tests (ALT) is to determine the reliability of the device tested in a moderate period of time (weeks or months). For this purpose, one of the parameters of the device under test is subjected to high levels of stress leaving the rest of the parameters working under nominal operation conditions.

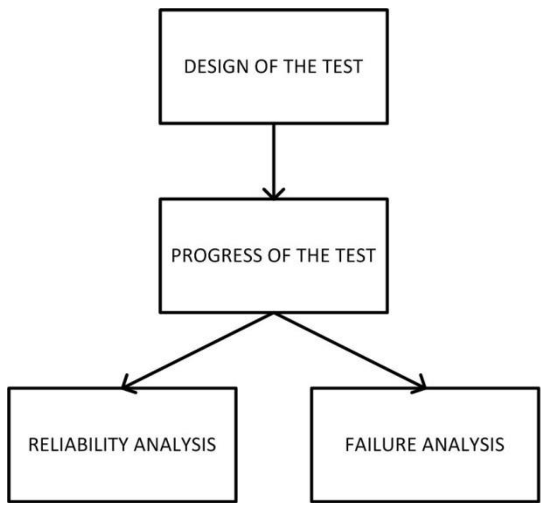

FIGURE 1. Sketch of the stages of the temperature accelerated life test carried out. This paper is focused on the reliability analysis stage.

The high levels of stress used in the tests force failures by accelerating the effects of natural aging. Thus, assuming a mathematical and physical reasonable statistical model which relates the lifetime to the level of stress through an acceleration factor, the life data from the ALT can be used to extrapolate the reliability functions and parameters under nominal stress levels.

The steps followed in our accelerated life tests have been classified into four stages as shown in figure 1: 1) design of the test, 2) progress of the test, 3) reliability data analysis and 4) failure analysis. In this paper we briefly describe the steps followed in stages 1) and 2), since they have been presented in detailed in [4]. In fact, this paper is focused on the reliability data analysis (stage 3). The failure analysis is under development and it will be presented in a further study.

DESIGN OF THE TEST

The following information needs to be determined in order to start with the experiment:

1. Nominal working conditions under concentration. These particular solar cells are expected to work inside an optical concentrator at 820 X and 80 ºC.

2. Current which has to be injected in darkness to emulate working conditions.
For that simulations with our 3D distributed model for triple-junction solar cells have been carried out [5], [6]. The criterion followed has been that the absolute value of current density through the junctions in darkness does not surpass at any point of the solar cell the current density photo-generated in the active area at 820 X [4]. Thus, the criterion followed avoids current over-stress. The maximum current level which fulfilled this requirement was 3.2 A. Therefore, 3.2 A were injected into the solar cells in order to emulate nominal photo-current conditions at 820 X.

3. Test temperatures.
It has been checked that the solar cell's packaging (without optical elements) was able to handle up to 170 °C. Therefore, solar cells have been tested at ($T_{Solar\ Cell}$): 119, 126 and 164 ºC.

4. Pre-test solar cells characterization.
The following characterization techniques were measured in all the solar cells in order to carry out the failure analysis when the tests end: 1 and 500 X illumination I-V curve, dark I-V curve, external quantum efficiency, electroluminescence mapping and X-ray transmission imaging.

PROGRESS OF THE TEST

The solar cells tested were divided into three groups and they were introduced into three climatic chambers at different temperatures (see figure 2). As pointed out above, in order to emulate working conditions 3.2 A have been injected into the solar cells heating them up to: 119, 126 and 164 ºC. After a period of current injection, all the solar cells were automatically disconnected from the current injection. After a temperature stabilization period, the dark I-V curve of each solar cell has been measured. Once all the solar cells had been measured, the current injection started and the cycle started again. This cycle has been repeated over and over until all the solar cells inside the climatic chambers failed. All the solar cells have presented catastrophic failures since they have drastically become into short-circuits.

FIGURE 2. Photograph of the set-up developed to carry out the temperature accelerated life test.

RELIABILITY DATA ANALYSIS

Statistical Analysis

Once all the solar cells have failed (they have turned into short circuits), the analysis of accelerated life test data can be carried out and consists of [7]:
1. Finding a life distribution model which describes the solar cells failures at different temperatures. We have used the Weibull distribution with two parameters (β and η).
2. Finding a life-stress model that quantifies the manner in which the life distribution changes across different temperatures. We have evaluated the life-stress model that fits better the results of the ALT. This is the well-known Arrhenius model, and thus, it is the one we have used.

3. Combining the life distribution and the life-stress model. The combined Arrhenius-Weibull model which has been fitted to the experimental data has the expression:

$$f(t,T) = \frac{\beta}{C \cdot e^{E_A/kT}} \cdot \left(\frac{t}{C \cdot e^{E_A/kT}}\right)^{\beta-1} \cdot e^{-\left(\frac{t}{C \cdot e^{E_A/kT}}\right)^{\beta}} \quad (1)$$

where: t is the time, T the temperature, f(t,T) the probability density function, β the shape parameter, η the scale parameter, C is a parameter of the Arrhenius model, E_A the activation energy and k the Boltzmann constant.

4. Fitting the Arrhenius-Weibull model to our failure distribution across the different temperatures tested. The Arrhenius-Weibull parameters that fit better the data obtained in the ALT have been calculated by the Maximum Likelihood Estimation (MLE) method. The data obtained have been:

- $\beta = 2.79$
- $C = 1.53 \cdot 10^{-17}$ hours
- $E_A = 1.58$ eV

In figure 3, the unreliability, F(t), as function of time (described by equation (2)) at every stress level used in the test is shown.

$$F(t) = \int_0^t f(t)dt \quad (2)$$

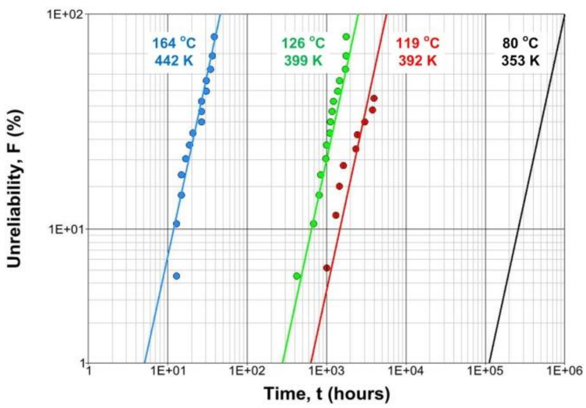

FIGURE 3. Unreliability as a function of time at every stress level used in the ALT. Experimental data are represented with dots (blue for the test of 164 °C, green for 126 °C and red for 119 °C) and the Arrhenius-Weibull model fitted for the different test temperatures are represented with a line. It also shows the extrapolated line (in black) for unreliability at the nominal operation temperature (80 °C).

The experimental data obtained from the accelerated life tests (dots) as well as the Arrhenius-Weibull model fitted (lines) are displayed. Figure 3 shows that the model fitted by the MLE method reproduces fairly well the data obtained experimentally in the accelerated life tests. Also, in figure 3 the extrapolated line (in black) for the unreliability at the specified nominal operation temperature (80 °C) is represented.

Reliability Prediction at 80 °C

Once we have fitted the Arrhenius-Weibull to the experimental data obtained from the ALT, we will use the model to extrapolate the performance of the solar cells at the nominal temperature of 80 °C.

The acceleration factor (A_F) is defined as a unitless number that relates the solar cell's life at an accelerated stress level to the solar cell's life at the nominal stress according to (3).

$$A_F = exp\left[\frac{E_A}{k}\left(\frac{1}{T_{Nominal}}\right) - \left(\frac{1}{T_{Stress}}\right)\right] \quad (3)$$

The acceleration factor obtained for the different stress temperatures with respect to the working temperature of 80 °C has been: A_F = 176, 401 and 21871 for the test at 119 °C, 126 °C and 164 °C respectively.

In figure 4, the reliability function, R(t), (described by expression (4)) at a nominal temperature of 80 °C (solid line) as function of time for continuous operation is represented.

$$R(t) = 1 - F(t) = \int_t^{\infty} f(t)dt \quad (4)$$

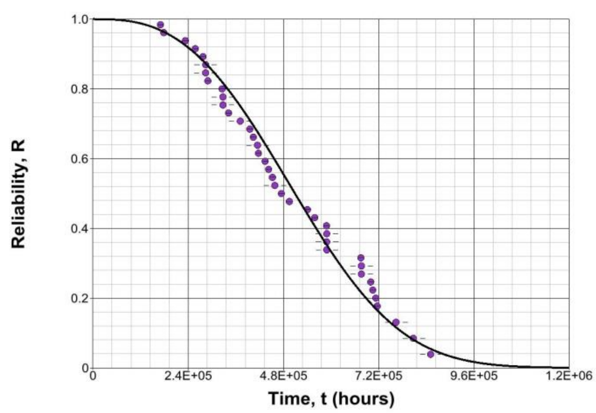

FIGURE 4. Reliability as function of time for a nominal working temperature of 80 °C (solid line) and the experimental data of the accelerated life tests transformed from the accelerated stress level to the nominal stress level (purple points).

Figure 4 also shows the experimental data of the accelerated life tests transformed from the accelerated stress level to the nominal stress level of 80 °C (purple points) by the corresponding acceleration factor (A_F)

obtained. Good fits between the reliability function extrapolated at nominal working conditions and the transformation of the experimental points are obtained.

In figure 5, the instantaneous failure rate function, h(t), evaluated in this test with the expression (5) at 80 ºC as a function of time is shown. In figure 5 we observe that the instantaneous failure rate function monotonically increases which corresponds to the wear-out failure part of the well-known bath-tube curve.

$$h(t) = \frac{f(t)}{R(t)} \quad (5)$$

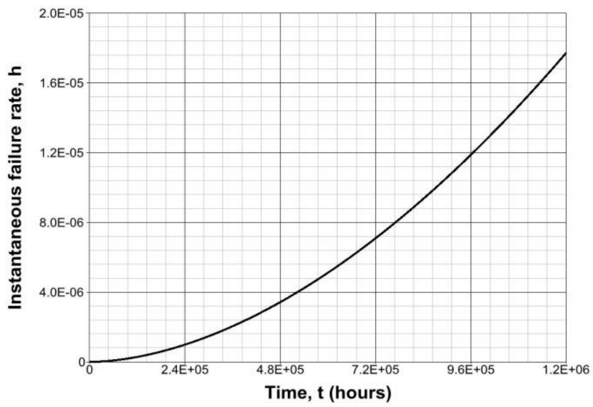

FIGURE 5. Failure rate function of the triple-junction solar cells for a nominal working temperature of 80 ºC.

By using the Arrhenius-Weibull model and assuming that the concentrator solar cells work 8 hours per day, at a concentration of 820 X (conditions emulated in the ALT) and at a temperature of 80ºC, the following reliability parameters are obtained:

- Warranty time for a failure population of 5%, W_t(5%Life) = 69 years
- Mean Time To Failure (MTTF) = 177 years

These results are very promising. However, it should be taken into account that we should check that the same failure mechanism is also promoted as the primary failure mechanism in other situations. This could be accomplished by exposing the solar cells to other stresses such as light intensity. Besides, it has to be also checked that this kind of failure is the same that appears in real life under nominal working conditions. Finally, it should be pointed out that these reliability results are only applicable to these particular solar cells with this packaging.

SUMMARY AND CONCLUSIONS

In this paper temperature accelerated life tests on commercial GaInP/Ga(In)As/Ge triple-junction concentrator solar cells have been carried out. The aging of the solar cells has been accelerated by stressing the solar cells in temperature. The nominal photo-generated current under a concentration of 820 X has been emulated by injecting current in darkness. The failure distribution at the different temperatures has been properly fitted to an Arrhenius-Weibull model. We have obtained a shape parameter β = 2.79 while the Arrhenius activation energy obtained has been E_A = 1.58 eV. We have used the Arrhenius-Weibull model to extrapolate the main reliability functions and parameters to the nominal working conditions. We have obtained that the reliability results at 80 ºC are very promising. In fact, for a nominal temperature of 80 ºC a longer than 30-year warranty could be offered. Finally, it should be pointed out that each commercial solar cell processing and encapsulation approach could exhibit different failure modes and consequently different reliability.

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