FAILURE RATE MEASUREMENT ON SILICON DIODES REVERSE POLARIZED AT HIGH TEMPERATURE

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ABSTRACT

This paper calculates the failure rate on reversed polarized silicon diodes with the aim to justify, experimentally, the rules of the European Space Agency (ESA) which are referred to the component life's extension, the reliability increase and the end of life performance enhancement, by using oversized devices (derating rules).

In order to verify the derating rules, 80 silicon diodes are used, which are reverse polarized in a high temperature environment. The diodes are divided in 4 groups of 20 diodes, applying a different voltage to each group, in order to relate the failure rate to the applied derating rule. The experiment described in this paper is developed using a temperature accelerated test to check the leakage current in reverse polarization (HTRB - High Temperature Reverse Bias), with the purpose of obtaining results applying an acceleration factor in order to reduce the test duration.

By using a thermal model of the whole system and the equations that describe the reverse polarized diode behaviour, it is possible to stress the 80 diodes up to very high temperature avoiding the runaway effect.

Finally, the failure rate is calculated and a revision of the derating rules are proposed by using the experimental result obtained.

1. INTRODUCTION

ESA (European Space Agency) uses rules to extend the life of the devices, thus guarantee the proper operation for the duration of the mission [1]. This practice, which oversizes the devices and makes them work below their maximum ratings, is known as "derating".

But these rules, mandatory in space missions, increase the economic cost, the weight and the size of the selected devices to use for the design. These rules also reduces the list of a available devices for design. Thus complicating the suitable selection of these devices (which are not always available for space).

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In the end, the selection of the needed devices becomes a difficult task and increases the cost of the development. Of course this assures a higher reliability.

For example, the derating rules established by ESA for a Schottky diode define maximum values not to be surpassed and are as follows:

- 75 % of maximum forward current,
- 75 % of maximum reverse voltage,
- 50 % of maximum dissipated power and
- a maximum junction temperature of 110 °C or 40 °C below the manufacturer's maximum rating, whichever is lower.

Thus, in the case of the reverse voltage, the maximum value permitted under derating conditions would be 75 % of the maximum reverse voltage specified in the datasheet of the manufacturer.

Additionally, NASA (National Aeronautics and Space Administration) also proposes derating rules for devices, although they are different, in some cases, from the rules proposed by ESA.

For example, the rules from NASA of 2003 [2], for the same Schottky diode of the last example, establishes the following deratings:

- 50 % of maximum forward current,
- 70 % of peak inverse voltage (PIV),
- 50 % of maximum peak current,
- 80 % of maximum junction temperature (does not exceed 125 °C or 40 °C below the manufacturer's maximum rating, whichever is lower).

And some years before, in 1991, NASA had published derating rules [3] that resembled those currently used by ESA, but different to the used nowadays. In the example of the Schottky diode, the former compulsory derating asked by NASA then was:

- 75 % of maximum reverse voltage,
- 50 % of maximum dissipated power and
- a maximum junction temperature of 110 °C.

Other references [4] also propose that the failure rate is related to the stress and follows the 5th power law, which says, for example, that an increase of a 15 % of the applied voltage to the device, implies doubling the failure rate.

Summarising, the derating rules proposed by ESA and NASA, and other laws also related to derating, applied to electronic devices, are all based on mathematical models and also in the practical experience. However, it is possible to consider that a 10 year long mission should have a different requirement than a mission that is only 6 months long, thus, the derating rules should be different. Also, when both rules (ESA's and NASA's) are compared, some differences are detected that could mean that the reliability of electronic devices is still not fully understood.

A more in depth research is therefore needed, to better understand the reliability of semiconductor devices, together with experimental results to verify this research. The following question should be answered: are derating the rules applicable to any mission? and, could these rules be updated with new results and in order to optimise cost, mass and volume of space missions? [5] [6]

The experimental results obtained that correspond to the failure rate as a function of the applied derating can be used to justify and/or update the existing derating rules applied in space missions.

2. EXPERIMENT DEVELOPMENT

This paper follows these steps:

- A) Selection of the device under test.
- B) Selection of the variable to analyse.
- C) Experimental setup.
- D) Auxiliary components.
- E) Proposed thermal model.
- F) Analysis of the acceleration factor.

The first task to do consist in selecting the device and the variable to test. The next task is to propose an experimental setup. Then all additionally needed components of the setup will be identified. Finally, the thermal model and the acceleration factor will be calculated in order to predict the results of the experiment.

These steps should guarantee positive experimental results showing the failure rate of the devices.

2.1. Selection of the device under test

In order to simplify the experiment, a diode is considered as a device under test (DUT), because other different devices, like transistors imply additional complexity. The final selection of the DUT is based on the diode list found in the EPPL (European Preferred Parts List) [7].

A commercial equivalent for each diode of this list is identified, and then, a selection is made keeping in mind,

availability, electric characteristics, package and price of this equivalent diode (see Tab. 1).

Table 1. Diode selection

EPPL	Commercial	Package	Price (€)
1N6642U	1N6642D2A	DLCC2	24
BYW81-200	DPG15I200PA	TO-220AC	1.23
BYW81-200	BYV79E-20	TO-220AC	0.98
BYW52-200	BYW51-200G	TO-220AB	0.76
BYW52-200	NO		
1N5811US	1N5811	PTH	
1N5806US	1N5806	DO-204AP	4.45
1N5416US	NO		
1N5417US	1N5417	PTH	
1N5418US	1N5418	PTH	
1N5420US	1N5420	PTH	
1N54189UR-1	NO		
STPS1045	STPS1045B-TR	D-PAK	0.47
STPS6045	STPS6045CW	TO-247	3.4
STPS40100	NO	TO-220AB	0.76
1N5822U	1N5822	PTH	
1N5615	NO		
1N5617	1N5617	PTH	
1N5619	1N5619	PTH	
1N5623	NO		
STPS20100	NO		
1N5416	NO		
1N5417	NO		
1N5418	NO		
1N5420	NO		
1N5806U	1N5806D2A	TO-220AB	14.76
1N5819U	1N5819HW-7-F	TO-220AB	0.24
1N5614	NO		
1N5616	NO		
1N5618	1N5618	PTH	
1N5550	NO		
1N5552	NO		
1N5554	NO		
BAS70	BAS70-05	SOT-23	0.03

After discarding the diodes which have no commercial equivalent or have a different package than SMD (in order to solder the device on a PCB to a copper plane), the diode STPS1045 is selected as the best option for this test, due to its size, package and price. Additionally, this diode is an European low voltage Schottky, which is commonly used in space missions in output rectifiers of 3.3 V and 5 V.

This diode has a maximum reverse voltage of 45 V, and a reverse leakage current of 1.8 mA at 100 °C (45 V).

2.2. Selection of the variable to analyse

ESA's diode derating rules consider: direct current, reverse voltage, dissipated power and junction temperature.

In the first analysis, the dissipated power and the junction temperature won't be studied, because these characteristics can be calculated as a function of the direct current and/or reverse voltage.

Figure 1. Setup

Finally, the reverse voltage (V_R) is chosen as a characteristic to analyse. The reverse current will be measured using a shunt resistor connected in series to the DUT and independently from the other diodes. Additionally, the influence of the self-heating effect is less important in reverse polarization than in direct polarization.

2.3. Experimental setup

Once the diode and the characteristic to analyse is chosen, it is proposed to carry out an accelerated test increasing the temperature [8], [9] y [10], also known as an HTRB (High Temperature Reverse Bias) test. The derating rules will be applied as reverse biased diode, limiting the maximum reverse voltage and it will be studied how this extends life of the devices.

In order to guarantee the thermal uniformity of all DUT, they must be soldered to the copper plane of the PCB as close to each other as possible, and placed inside a climatic chamber, which will control the ambient temperature surrounding the devices and all its setup (see Fig. 1).

During the test continuous reverse voltage stress will be applied to the diodes reverse and temperature will be kept constant.

The total population of diodes used in this experiment is 80, which will be divided in 4 groups of 20 diodes and each group is reverse biased with a different voltage (V_R). In order to obtain results, that could show which is the most convenient derating to apply, the following reverse voltages (V_R) are proposed:

- $V_R = 100\%$ (45 V)
- $V_R \approx 80\%$ (36 V)
- $V_R \approx 50\%$ (24 V)
- $V_R \approx 30\%$ (12 V)

2.4. Auxiliary components

To measure the reverse leakage current (I_R) that appears when the diode is reverse polarized, which is the variable

Figure 2. Thermal diagram

to analyse, a shunt resistors will be used in series with each diode.

The value of this shunt resistor must maximize the measurement resolution and, at the same time, the voltage drop should not interfere in the experiment ($V_{R_{shunt}} < 2\%$ of the voltage V_R), then finally, the shunt resistor's value selected are:

- $V_R = 45\text{ V} \Rightarrow 75\ \Omega$
- $V_R = 35\text{ V} \Rightarrow 108.33\ \Omega$
- $V_R = 24\text{ V} \Rightarrow 390\ \Omega$
- $V_R = 12\text{ V} \Rightarrow 390\ \Omega$

2.5. Proposed thermal model

With the aim of guaranteeing that the DUT does not reach the maximum junction temperature and/or thermal runaway due to self-heating during the experiment, the operating temperature for the HTRB must be chosen using an appropriate thermal model of the setup.

To do this, the thermal resistance from junction-to-case ($R_{thj-c} = 3\text{ °C/W}$) and from case-to-ambient ($R_{thc-a} = 56\text{ °C/W}$) is obtained from the datasheet of the DUT. This last parameter depends on the copper area which the DUT is soldered to.

These constants are included into the thermal diagram of the used setup, obtaining thus the thermal model (see Fig. 2).

On the other hand, from the I_R vs. V_R curve of the datasheet of the DUT (see Fig. 3), the I_R values can be obtained for different points of T_j (25 °C, 50 °C, 75 °C, 100 °C, 125 °C and 150 °C) for the four used values of V_R (45 V, 35 V, 24 V and 12 V) (see Fig. 4). Next, with these values, it is possible to obtain the equations of the regression curves given by any curve fitting software, by using 5th order (see Fig. 4 and equations 1, 2, 3 y 4), for each of the four reverse voltages of this test.

With these four equations, being $V_R = 45\text{ V}$ the voltage with more self-heating influence in the junction temperature, a recursive simulation is carried out, using

Figure 3. Relationship I_R vs. V_R found in the DUT's datasheet.

the equation of the dissipated power of the diode (Eq. 5) and the expression that relates T_j with this dissipated power (Eq. 6) in order to verify the diode does not thermally runaway. In this case we can determine the maximum operating temperature to stress the diodes, before thermal runaway occurs.

$$V_R = 45 \text{ V} \Rightarrow I_R(\text{mA}) = 3.7248 \cdot 10^{-06} \cdot T_j^5 - 1.2997 \cdot 10^{-03} \cdot T_j^4 + 1.8231 \cdot 10^{-01} \cdot T_j^3 - 1.2068 \cdot 10^{+01} \cdot T_j^2 + 3.6960 \cdot 10^{+02} \cdot T_j - 4.06500 \cdot 10^{+03} \quad (1)$$

$$V_R = 35 \text{ V} \Rightarrow I_R(\text{mA}) = 1.7916 \cdot 10^{-06} \cdot T_j^5 - 6.1835 \cdot 10^{-04} \cdot T_j^4 + 8.7004 \cdot 10^{-02} \cdot T_j^3 - 5.8015 \cdot 10^{+00} \cdot T_j^2 + 1.7912 \cdot 10^{+02} \cdot T_j - 1.9820 \cdot 10^{+03} \quad (2)$$

$$V_R = 24 \text{ V} \Rightarrow I_R(\text{mA}) = 2.6767 \cdot 10^{-06} \cdot T_j^5 - 9.6205 \cdot 10^{-04} \cdot T_j^4 + 1.3530 \cdot 10^{-01} \cdot T_j^3 - 8.9491 \cdot 10^{+00} \cdot T_j^2 + 2.7331 \cdot 10^{+02} \cdot T_j - 3.0008 \cdot 10^{+03} \quad (3)$$

$$V_R = 12 \text{ V} \Rightarrow I_R(\text{mA}) = 5.8795 \cdot 10^{-07} \cdot T_j^5 - 1.7472 \cdot 10^{-04} \cdot T_j^4 + 2.2493 \cdot 10^{-02} \cdot T_j^3 - 1.4188 \cdot 10^{+00} \cdot T_j^2 + 4.2512 \cdot 10^{+01} \cdot T_j - 4.6400 \cdot 10^{+02} \quad (4)$$

$$P_D(\text{W}) = I_R \cdot V_R - R_{shunt} \cdot I_R^2 \quad (5)$$

where,

- P_D is the dissipated power in W
- I_R is the reverse leakage current in A
- V_R is the reverse voltage in V
- R_{shunt} is the value of the shunt resistor in Ω

Figure 4. Values extraction of I_R as a function of T_j and V_R , and adjustment to 5th polynomial order.

Figure 5. Results of the recursive simulation where a thermal runaway is observed for $T_j = 110^\circ\text{C}$ and $T_j = 120^\circ\text{C}$

$$T_j(^{\circ}\text{C}) = T_a + (R_{th_{j-c}} + R_{th_{c-a}}) \cdot P_D \quad (6)$$

where,

- T_j is the junction temperatures expressed in $^{\circ}\text{C}$
- T_a is the operating temperature expressed in $^{\circ}\text{C}$
- $R_{th_{j-c}}$ is the thermal resistance from junction-to-case expressed in $\text{W}/^{\circ}\text{C}$
- $R_{th_{c-a}}$ is the thermal resistance from case-to-ambient expressed in $\text{W}/^{\circ}\text{C}$
- P_D is the dissipated power in W.

The result given by the recursive simulation (see Fig. 5) is that, with an operating temperature of about 110°C , diodes blocking $V_R = 45 \text{ V}$ reach the thermal runaway ($T_j > 150^\circ\text{C}$) destroying the silicon junction of the semiconductor. Therefore, the temperature of the experiment is reduced by 10°C and so fixed at 100°C , programming the climatic chamber used.

2.6. Analysis of the acceleration factor

As said before, the experiment shown in this paper stressed the diodes after derating their limits [1], which makes more difficult to obtain a failure. To observe a failure an accelerated test will be done.

By using the Arrhenius' equation (Eq. 7) in order to calculate this acceleration factor, customized by NASA (Eq. 8), where the constant of activation energy is ($E_A = 0.2656$ eV) [11] and knowing the operating temperature of the experiment ($T_a = 100^\circ\text{C}$), the obtained acceleration factor is equal to 8 units. For example, 1000 hours of this test are equivalent to 8000 hours of operation of the DUT (at 25°C).

$$A_T = \frac{\lambda_{T1}}{\lambda_{T2}} = e^{\left[\frac{E_A}{k} \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]} \quad (7)$$

where,

- A_T acceleration factor
- T_1 y T_2 is the temperature 1 and 2 respectively in $^\circ\text{C}$
- λ_{T1} and λ_{T2} is the failure rate at temperature 1 and 2 respectively
- E_A is the activation energy in eV
- k is the Boltzmann constant in eV/ $^\circ\text{C}$

$$\pi_T = \frac{\lambda_{T_j}}{\lambda_{25^\circ\text{C}}} = e^{\left[-3091 \left(\frac{1}{T_j - 273} - \frac{1}{298}\right)\right]} \quad (8)$$

where,

- π_T is the acceleration factor
- λ_{T_j} is the failure rate at the operating temperature
- $\lambda_{25^\circ\text{C}}$ is the failure rate at 25°C
- T_j is the junction temperature of the semiconductor in K

3. RESULTS

Until now, the results (see Fig. 6) show a quite stable behaviour of the reverse leakage current for the four derated diode groups. In a first transient stage, an increase of the reverse leakage current is observed until it reaches the steady-state after the adjustment of temperature of the climatic chamber up to 100°C .

The standard calculation method to obtain the failure rate is shown in Eq. 9.

Figure 6. Reverse leakage current evolution

$$\lambda = \frac{x}{TDH \cdot AF} \quad (9)$$

where,

- λ is the failure rate in number of failures / 10^6 hours
- x is the number of failures
- TDH is the summation of the number of units in operation multiplied by the time of operation.
- AF is the acceleration factor

And, additionally, the mean time to failure is defined as:

$$MTTF = \frac{1}{\lambda} \quad (10)$$

where,

- $MTTF$ is the mean time to failure (time to fail of 63% of the population).
- λ is the failure rate.

Although, degradation has not been detected and no broken diodes appeared after 4887 hours of test, and the exact value of the failure rate cannot be obtained. Anyhow, is possible to obtain comply with predicted maximum value of the failure rate in case one diode brakes down just one hour after measuring the devices. Finally, the failure rate can be calculated by using $x=1$, $TDH = 80$ devices multiplied by 4887 hours, and $AF = 8$ (as previously calculated) in Eq. 9:

$$\lambda < \frac{1}{80 \cdot 4887 \cdot 8} = 0.320/10^6 \quad (11)$$

The mean time to failure (MTTF), in this case, using the equation 10 is:

$$MTTF > \frac{1}{\lambda} = 3\,127\,680 \text{ h} \quad (12)$$

4. CONCLUSION

This paper studies the effect of the derating rules, applied to reversed polarized Schottky diodes, to the failure rate with the aim of comparing the derating rules published by ESA or NASA with the experimental results.

A high temperature reverse bias experiment is developed using a population of 80 diodes divided in 4 groups (4 different derating values) of 20 diodes each, with the aim of measuring the leakage current of every single diode reverse polarized.

With 4887 h under test at 100 °C, which is equivalent to more than 39 000 h at 25 °C, no degradation has been detected and no broken diode happened, obtaining a maximum value of the failure rate equal to 0.320 failures / 10⁶ h.

The absence of failures in the diodes, after 4887 h under test at 100 °C with a derating between 100 % and 30 %, means that in short term (taking into account the scope of this work with only 4887 h under test) the derating has not reduced the failure rate.

This fact points out the derating rules should be reviewed in order to take account the duration of the mission, for instance, the increase of the derating values at least in 6-months missions.

5. REFERENCES

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