Microelectronics Reliability xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Reliability-oriented environmental thermal stress analysis of fuses in power electronics

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ARTICLE INFO

Article history:
Received 23 May 2017
Received in revised form 26 June 2017
Accepted 30 June 2017
Available online xxxx

ABSTRACT

This paper investigates the thermo-mechanical stress experienced by axial lead fuses used in power electronics. Based on some experience, the approach used in this paper is pure thermal cycling, and the found failure mechanisms have been investigated through X-ray imaging. A two-step analysis, i.e. microscopic inspection and FEM thermo-mechanical simulation have been carried out based on the real geometry, including core and isolation materials, as well as the arc quenching one, which is typically quartz sand. The failure mechanism hypothesis of higher temperature variation at the end hole of the fuse element has been confirmed thanks to the analysis performed. Finally, the fatigue analysis is presented obtained by FEM-based fatigue tool.

1. Introduction

Fuses are widely used in electronic and power electronic circuits to prevent damage in the components and systems because of over-currents [1]. A fuse consists of a thin notched conductor – conventionally a high conductive metal like silver – end caps, and an insulator body filled with an arc quenching material. In the case of short circuit, over current is established that leads to a high temperature and eventually melting the thin conductor due to the joule heating. Hence, an electric arc is initiated and breaks the fault current.

The main parameters that define the characteristics of the fuses are the breaking capacity, rated voltage, rated current and i^2t [2]. In the normal operation of fuses, these parameters are given in the datasheet and they are supposed to be constant in the lifetime of the fuse. Moreover, the fuses are designed to operate in emergency conditions and not in normal operations. However, fuses are prone to failures or malfunctions originated from thermal stresses by self-heating and ambient temperature variations.

It has also been proven that the reliability of power electronic components is a critical factor that determines the lifetime of the converter system [3]. The main stressors that affect the lifetime of components are temperature, humidity, and vibration [4]. Depending on the operational and environmental conditions, components experience different types and levels of stresses [5]. Although research works prove that the power semiconductor devices and film capacitors are the components with higher failure rates, other power components like fuses are also important to be studied from reliability point of view as they are functional and critical components if a failure occurs [6].

Today, thumb rules are still dominating the design process of fuses. That means that there are no reliability-oriented instructions in the design of e.g. notches or holes in the element of fuses. In other words, the reliability of fuses as critical components in power electronic circuits, which should not fail in any case other than the over-current, has not been fully covered in research. Just a few studies have been carried out to study the electrical performance of fuses by load current cycling [7–9].

As mentioned earlier, temperature is among the main stressors in the power electronic components. In this paper, the impact of temperature cycling on thermo-mechanical stresses in a fuse element is studied. Passive thermal cycling tests are carried out to identify the weak point in the fuse and to determine the ambient temperature cycling parameters, which shorten the lifetime of the fuse. In the following, finite element-based simulations are implemented to analyze the test results. Thermo-mechanical simulations and fatigue analysis enable the development of the lifetime model for the fuse, which can be used in normal and harsh environment i.e. desert fields.

2. Thermal cycling tests

The fuse structure under study consists of a thin silver strip with 5 notched holes soldered to copper end caps and covered with a ceramic tube that is filled with sand.

2.1. Thermal shock test

In order to test the reliability of fuses in respect to thermal cycling, different fuses are mounted on PCBs and they are placed in dual-chamber thermal shock equipment with the following parameters:

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http://dx.doi.org/10.1016/j.microrel.2017.06.089
0026-2714/© 2016 Published by Elsevier Ltd.

Please cite this article as: A.S. Bahman, et al., Reliability-oriented environmental thermal stress analysis of fuses in power electronics, Microelectronics Reliability (2016), http://dx.doi.org/10.1016/j.microrel.2017.06.089

- $T_{lower} = -40$ °C
- $T_{upper} = +125$ °C.

The duration of each step is 30 min. Therefore, the thermal cycling period will be 1 h. Since the transition from upper to lower temperature is done by moving the Device Under Test (DUT) from the hot chamber to the cold one, the temperature stimulus can be considered as an ideal step. The PCB consists of 4 layers with 70 μm of copper on the inner layers and 35 μm of copper on the outer layers. Both the outer and inner layers are made with copper in order to mimic a standard product PCB. In this test, axial lead fuses are mounted on the PCB with a rated current of 30 A and a rated voltage of 500 V, a breaking capacity of 30 kA and nominal i^2t of 203 A^2 s. 10 fuses are soldered vertically and 10 fuses are soldered horizontally. At regular intervals, i.e. number of cycles, the resistance of the fuse is measured by a simple contact/no contact measurement. The measurements are done at the room temperature. The results for the horizontally soldered fuses state that two fuses failed after 371 and 1000 cycles. The results for the vertically soldered fuses state that 5 fuses failed after 191, 231, 271, 271, and 431 cycles respectively. Some items have been removed from the test in order to perform X-ray inspection. An X-ray image of the fuse failed at 231 thermal shock cycles is shown in Fig. 1. As it can be seen, the fuse element is broken in the notch of a hole close to the end cap.

2.2. Mission profile defined test

To get a more realistic thermal cycling data, a worst case has been defined. To define the profile, the average temperature cycling in the most demanding locations on earth has been taken. Probably one of the most demanding locations is in the deserts where the night temperature is very low and the day temperature is very high. So, Dubai is chosen as the model for the worst case temperature profile. This profile is a typical desert profile and considered as the worst case that is shown in Table 1.

In the desert thermal cycling scenario, 36 fuses which were laid out on a PCB in horizontal/vertical positions are tested. The fuse temperature load consists of 3 contributions:

- Fuse self-heating because of 10 A load current with temperature rise of $\Delta T_{(10\ A)} = 20$ °C and duration of 2 min to get the temperature to steady-state;
- Control box internal temperature with temperature rise of $\Delta T_{(internal)} = 15$ °C because of the fuse load current and duration of 1–2 h to get the temperature to steady-state;
- "Desert" control box ambient temperature, in 12 h:

  $\Delta T_{(ambient)} = 25–70$ °C $= 45$ °C at 120 cycles

  $\Delta T_{(ambient)} = 25–60$ °C $= 35°$ at 150 cycles

  $\Delta T_{(ambient)} = 25–55$ °C $= 30°$ at 90 cycles

  where "one year" profile is defined by 120 cycles + 150 cycles + 90 cycles = 360 cycles totally.

Table 1
Desert thermal cycling scenario.

Test scenario	Temperature diff. day-night	Design life success criteria
Worst case 40 °C ambient	$\Delta T = 45$ °C at 4 months/year $\Delta T = 35$ °C at 5 months/year $\Delta T = 30$ °C at 3 months/year	10 years lifetime 1 cycle per day

The warm-up/cool-down duration time is defined to be 30 min in order to reduce the test time and the maximum $\Delta T_{fuse}/dt$ is 4–6 °C/min. Consequently, the acceleration factor is equal to 24, i.e. an hour per day equivalent. The fuse resistances are measured every 360 cycles and the success criteria is defined by 360 × 10 cycles = 3600 cycles = 10 year equivalent lifetime. Fig. 2 shows the fuses tested in the chamber. The failed fuse results state 1 × 2.5 years, 1 × 3.5 years, 1 × 4.5 years, 3 × 6.5 years, and 2 × 7.5 years. The failures in the fuses show that even in a pure passive thermal cycling test, some fuses fail below the 10 year lifetime that is lower than the success criteria.

3. FEM thermo-mechanical simulation analysis

In order to verify and analyze the results obtained from thermal cycling tests, the Finite Element Method (FEM) based thermo-mechanical simulations are carried out. A schematic of the opened fuse modelled in SolidWorks® is shown in Fig. 3. As it is seen, one end of the fuse element (silver strip) is trapezoidal that is due to the manufacturing reason to place the strip in the tube and to solder it to the end caps.

ANSYS® is used to model the thermo-mechanical stress in the fuse. The materials thermal and mechanical properties are set to be temperature dependent. A temperature profile of 25–80 °C with the warm-up/cool-down time approximated at 30 min is forced to the fuse body as shown in Fig. 4. However, it has been obtained by simulations that the minimum time to maintain the fuse strip at warm/cool temperature is 3 s for the temperature distribution along the fuse to become uniform before the application of a new temperature ramp. The heat is mostly transferred inwards through the end caps because the ceramic tube has a much lower thermal conductivity compared to the copper caps. A temperature distribution of the fuse element is shown at warm-up period in Fig. 5.

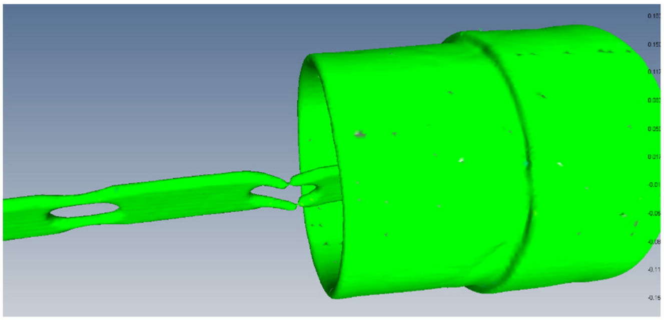

Fig. 1. 3D X-ray of a fuse, which has been subjected to 231 thermal shock cycles.

Fig. 2. The fuses being tested in the desert scenario.

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