Novel Safe-Life concept for circuit protection devices

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INTRODUCTION

SCHURTER introduces a novel redundancy concept for circuit protection solutions for high reliability applications. This so-called Safe-Life concept aims to solve the disadvantage of the current limiting resistor commonly used in redundancy systems for circuit protection devices. It radically reduces ohmic-losses of the redundancy system, and quickly and safely isolates a fault circuit from the healthy circuit. SCHURTER recently conceived and characterized a function model of this concept. In this paper, the results of the first function model are discussed. The results are promising and demonstrate the potential to realize the most compact Safe-Life module using an irreversible microswitch based on MEMS technology for high-reliable application where space on PCB, costs and safety is most critical.

PROBLEM & MOTIVATION

The commercial space industry often prefers COTS components instead of the traditional space grade versions due to shorter lead time and cost advantage. Nevertheless, they have also to cope with the lower reliability of unscreened COTS components. Arranging two or more components in parallel represents a common approach to increase the system's reliability and availability. This redundancy concept is also considered with circuit protection devices such as fuses. Two or more similar fuses are set in parallel. In order to ensure that the load current is controlled by the primary fuse during normal operation, a series resistor significantly limits the current through the back-up fuse. Typically, this resistor's electric resistance is at least 10-times bigger than the fuses' resistance. Consequently, the back-up current is limited to less than 10% of the load current during normal operation. This redundancy concept is also called warm redundancy, consider Figure 1. However, one disadvantage of this concept is the high-power dissipation of the current-limiting series resistor in the case the back-up fuse takes control of the load current because of a failed or consciously isolated primary fuse. In such situation, the load current through the series resistor induces, proportional to its electrical resistance value, significantly higher power losses than during the normal operation. This leads to heat constraints in the thermal management concept of the spacecraft. A second need is to sporadically reset a specific sub-system in a spacecraft in the case of an unexpected situation or to proactively disconnect the load circuit in case of a critical but low overcurrent where a fuse usually fails to quickly and predictable isolate the fault circuit. Such functionalities are typically realized by using a semiconductor-based switching device. However, this device is first, less reliable than a simple fuse due to its overall higher design complexity and second, it can't galvanically isolate a fault circuit as a fuse it does. Today, in some of these applications a fuse as a fail-safe device is placed in series to the semiconductor switch to properly isolate a circuit in the case of a dangerous fault.

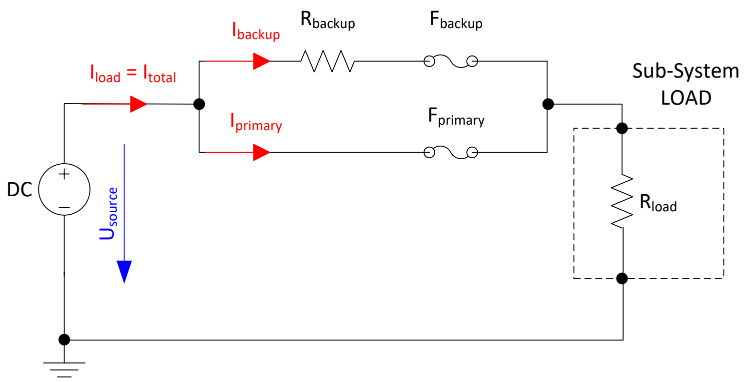

Figure 1. Warm redundancy concept with two fuses and current-limiting resistor[2].

SCHURTER responds to these challenges space customers face with the invention of a novel Safe-Life concept. The core technology of this concept represents an irreversible microswitch to replace the current limiting resistor in the back-up circuit, shown in Figure 3. The irreversible microswitch allows an interrupt-free and safe change of state as it ensures galvanic isolation between the primary and the back-up line in the back-up operation (State B).

The state machine in Figure 2 illustrates the state change from primary operation (State A) to the back-up operation (State B) which can be triggered by a failed or consciously tripped circuit protection device.

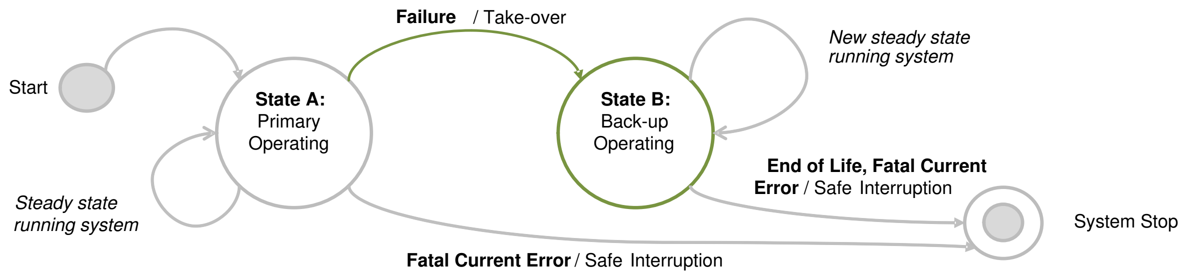

Figure 2. States of the Safe-Life concept[2].

The objective of the study was to design a highly miniaturized module incorporating an irreversible microswitch that ensures low electrical contact resistance below 10 mΩ and can continuously carry currents up to 10 A. The target solution is a universal three-terminal device, intended to address galvanic isolation constraints and enable the integration of various circuit protection technologies, such as fuses or semiconductor-based switching devices, within advanced redundancy concepts.

DESIGN OF THE SAFE-LIFE CONCEPT

Figure 3 illustrates the concept as a three-terminal module to be positioned behind the primary and back-up circuit protection devices.

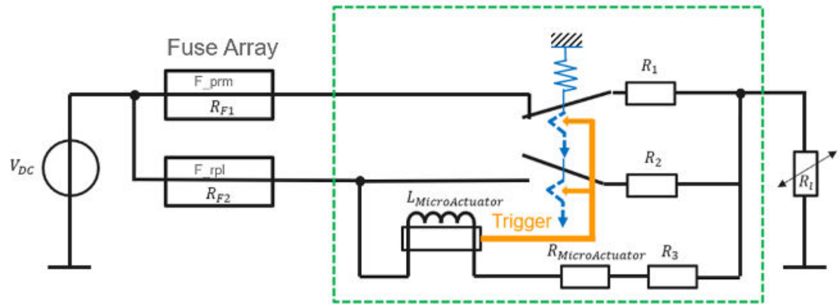

Figure 3. The novel Safe-Life concept illustrated as three-terminal module – green dotted box.

The core components of the module are the two switching contacts: one normally closed (NCC) for the primary circuit and one normally open (NOC) for the back-up circuit. An electromagnetic actuator is supplied in the back-up circuit, releasing the pre-loaded contacts in the event of a failure in the primary circuit. A series resistance, R_3, is positioned in series to the actuator, $R_{MicroActuator}$, to adjust the threshold current for releasing the contacts, depending on the characteristics of the failure to being addressed. R_1 and R_2 represents series resistances in the electrical circuits between the contacts and the output terminal.

The two contacts, NOC and NCC, along with the spring array - comprising the main, travel and split spring, and the mechanical locking system - constitute the so-called irreversible microswitch system. This system is based on MEMS technologies and entirely implemented on a single Si-chip as shown in the left illustration in Figure 4.

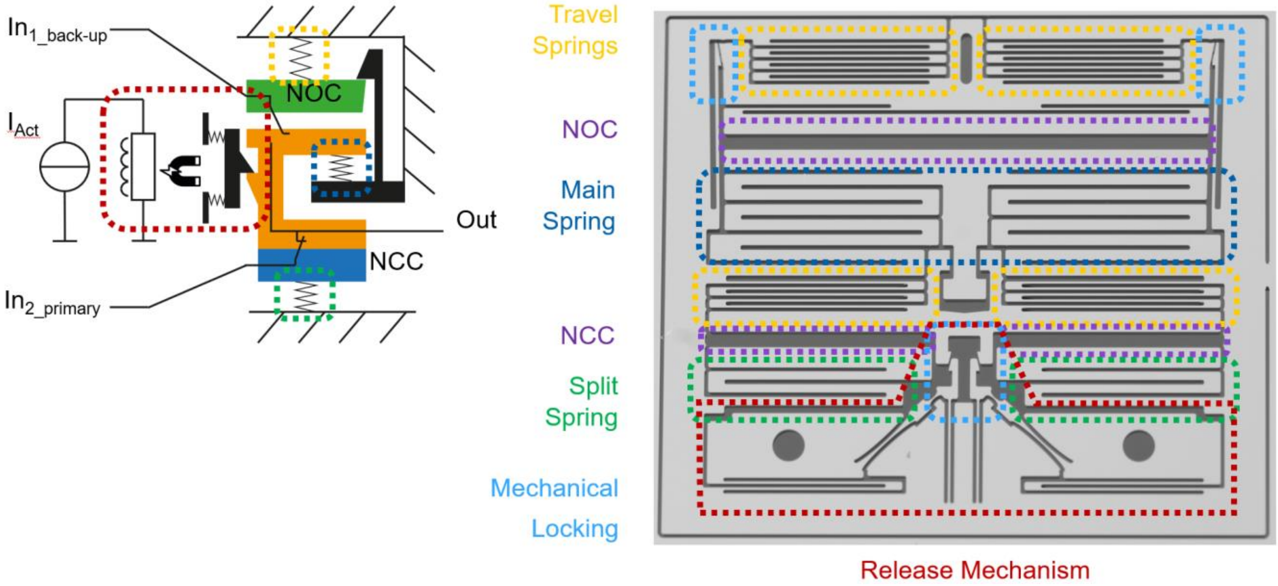

Figure 4. Functional concept of the irreversible microswitch system on a single Si-chip.

The electromagnetic actuator is part of the mechanism for releasing the mechanical lock of the preloaded springs and is directly mechanically attached to the Si-chip using a two-component epoxy. The actuator consists of a U-shaped yoke and a bar-shaped armature, both made from ferromagnetic materials, with a defined air gap to facilitate magnetic actuation. The second side of the Si-chip is attached to a standard two-sided PCB frame using an electrically conductive silver epoxy to establish a solid electric contact between the metal areas on the Si-chip and the terminals on the PCB frame.

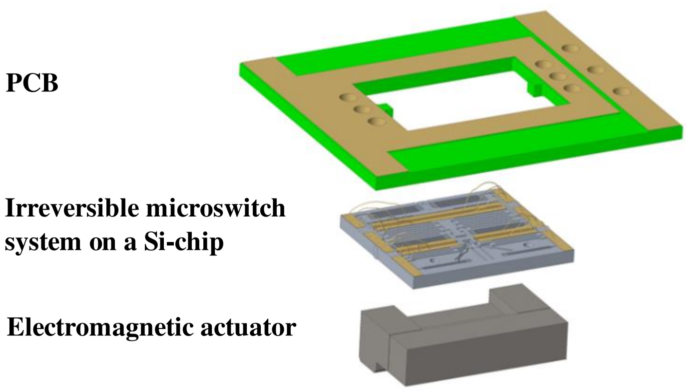

Figure 5. Assembly view of the Safe-Life module.

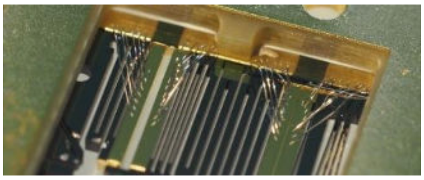

Figure 6. Detail of the assembly with Au-wire bonds that electrically connect the ENEPIG-finished contacts to the frame of the Si-chip.

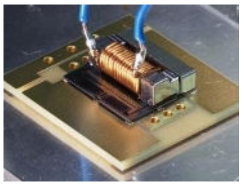

Figure 7. Fully assembled Safe-Life module.

CHARACTERIZATION AND PERFORMANCE

The scope of this study was narrowed down to address four key objectives: minimizing ohmic losses, ensuring compatibility with components like fuses up to 15 A, providing galvanic isolation of the failed circuit, and achieving a compact device size. Table 1 below lists these quantified objectives.

Objectives	Requirements (quantified)
Low ohmic loss	Electrical resistance < 5.3 mΩ
	Total power dissipation < 1.2 W
Compatibility with rated components up to 15 A	Continuously operating at 15 A
Safe	Galvanic isolation
Device size	< 1 cm^3

Table 1. Quantified objectives

In the first step, the electrical performance was characterized by measuring the cold resistance of the contacts and the assembled devices. In the second step, design limit tests were conducted to determine the maximum continuous current and power dissipation.

a. Cold Resistance

Two sets of cold resistance measurements, based on the 4-points measurement method, were conducted: first on PCB - based contacts with an ENEPIG surface finish, and then on the assembled irreversible microswitches. The PCB contacts, with contact areas ranging from 0.01 mm² to 9.0 mm² and contact forces from 0.05 N to 5.0 N, exhibited resistances between 10 mΩ and 1 mΩ respectively. The microswitches showed a median resistance of 3.1 mΩ, which aligns with the expectations based on the PCB tests.

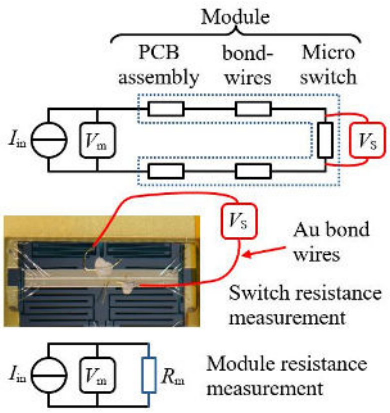

Figure 8. Microswitch resistance and module resistance measurement.

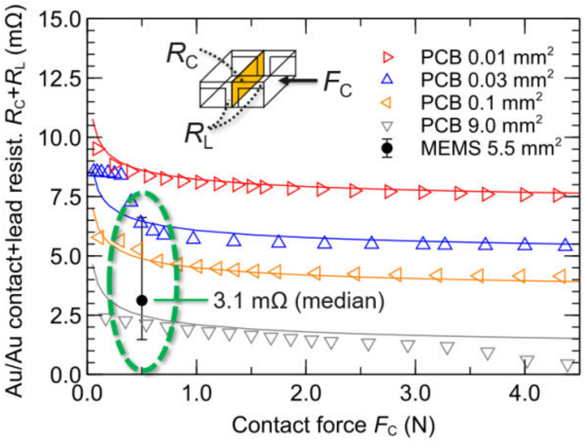

Figure 9. Measured resistances as a function of contact force for PCB tracks of different sizes with ENEPIG plating[2].

b. Design Limit – Current Step Test

In total five devices were tested, including operation at current steps starting at 1A up to 10 A and stress tests beyond 10 A until failure. The devices demonstrate linear voltage drops at currents up to 10 A, meaning the samples are in a stable condition. The calculated mean value in this operating area is 30 mΩ.

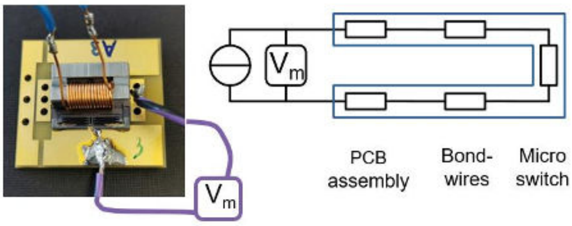

Figure 10. Current step test measurement

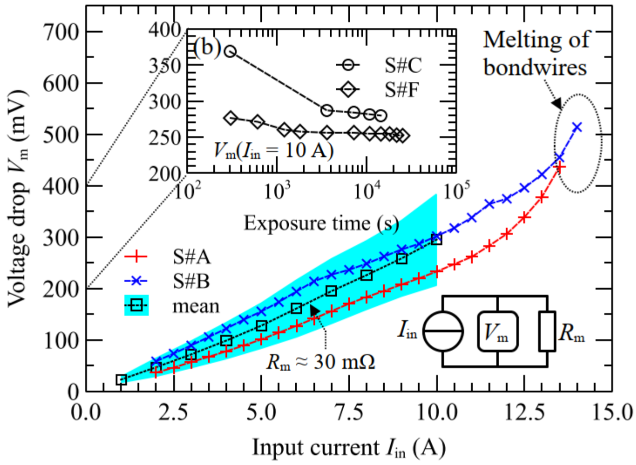

Figure 11. Current Step Test of the fully assembled module.

Long-term testing at a constant current of 10 A for over 4 hours revealed a decrease in module resistance during the first hour of operation, after which the resistance stabilized, as shown in the small window (b) in Figure 11. This indicates that the device can maintain stable performance over extended periods, although further investigation into potential risks is necessary. Devices exposed to currents exceeding 10 A failed at currents of up to 13.5 A. The predominant failure observed was bond wire melt-down, illustrated in Figure 12, which highlights the limits of the current device evolution.

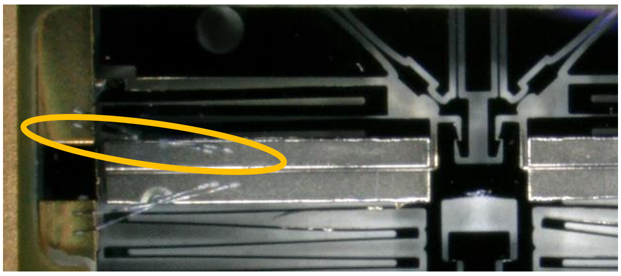

Figure 12. Wire bond melt down at current level 13.5 A, highlighted in orange area

CONCLUSION

The development of the novel Safe-Life design represents a significant achievement in the field of advanced redundancy concepts. A low mean contact resistance of 3.1 mΩ was achieved, however the total warm resistance of 30 mΩ results in a power dissipation of 3 W at 10 A, which is clearly outside the objective of 1.2 W at 15 A. Therefore, significant design improvements are required. The results and findings of the first function model are summarized in Table 2.

Objectives	Requirements	Results / Findings
Low ohmic loss	Electrical resistance < 5.3 mΩ	Contact resistance 3.1 mΩ Total warm resistance 30 mΩ
	Total power dissipation < 1.2 W	3 W at 10 A
Compatibility with rated components up to 15 A	Continuously operating at 15 A	Continuous operating up to 10 A
Safe	Galvanic isolation	Yes
Device size	< 1 cm^3	Yes

Table 2. Results and Findings

The rigorous characterization tests have provided valuable insight into the current limitations of the design, but also an indication of the potential of this concept to achieve the target product. Informing future improvements are therefore the following:

- Reduction of the total electrical resistance
- Wire bond to connect the contacts to the frame to be reconsidered.
- Improving design robustness to withstand mechanical shock/vibration (Not yet addressed)
- Miniaturization/Replacement of the electro-magnetic
- Simplification of the design to reduce the manufacturing costs

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[2] B. Zemp, P. Straub, and T. Flury "CIRCUIT PROTECTION SOLUTIONS FOR SPACE APPLICATIONS," *Space Passive Component Days 2016, Noordwijk, The Netherlands,12-14 October 2016*