A Motor Drive Electronics Assembly for Mars Curiosity Rover: an Example of Assembly Qualification for Extreme Environments

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1. Introduction

For NASA Mars Curiosity Rover or Mars Science Laboratory (MSL), a motor drive electronics assembly was needed to be placed outside of the spacecraft and, therefore, was exposed to a radiation environment and a temperature range as wide as from -120°C to 125°C, which is beyond the military standard temperature range of -55ºC to 125ºC. The performance and reliability of the electronics and packaging technologies are the major concern and challenge for the assembly under this wide temperature range. The design-for-reliability approach and the application-specific qualification methodology, developed for the electronics and packaging of the assembly for the Mars Curiosity Rover, has provided the critical path for the technology infusion and mission success.

In this paper, the technology development and infusion of the motor drive electronics assembly, along with the technology qualification and space qualification, is described and detailed. The process is an example of the qualification methodology for extreme environments and for assemblies which requires a high level of reliability.

2. Technology Development and Infusion

2.1 Electronics

A list of electronics for the motor drive electronics system was selected based on the potential survivability and reliability of the electronics technology, and encompassed a number of discrete transistors, capacitors, resistors, digital gates, mixed signal circuits, and operational amplifiers.

A functional go/no-go testing down to as low as -180°C was first conducted to characterize the electronics at low temperatures [2]. While the majority of the electronics selected were functional and survived the low temperature life test, all the op-amps tested failed to meet the performance requirements of the assembly over the wide temperature range. Therefore, the technology development effort was focused on the design, fabrication and qualification of an op-amp to ensure performance, radiation and long term reliability requirements under the wide temperature range of -140°C to +125°C.

<u>Design for performance:</u> The goal was to develop an op-amp that minimizes variation in key performance parameters over a wide temperature range of -150°C to 125°C. Since it is desirable to simultaneously minimize variations in both small- and large-signal performance of the op-amp over the wide temperature range, a constant inversion coefficient (*IC*) current reference approach was developed, over either constant g_m bias optimum for minimizing variations in small-signal performance or constant current *I* bias optimal for minimizing the variations in the large-signal performance of the circuit [3]. Table 1 gives an example of slew rate and bandwidth ratios between -140°C and 85°C, evident that the constant *IC* approach provides lower overall temperature dependence.

<u>Design for reliability:</u> To ensure rad-hardness, a certified 3.3V SOI process was chosen as the fabrication of the op-amp. However, the assembly was required to be a 5V board and hence the op-amp needed to be 5-V compatible. The 5-V system level compatibility combined with reliability requirement complicated the design of the op-amp. Extensive simulation was used to analyze the operating bias conditions of the transistors under the worst case supply bias condition to determine that all voltage swing across all the terminals of the transistors were limited to about 3.5 V. In the case of excessive V_{DS}, cascode devices were added and for excess V_{GS}, the voltage level was clamped [3]. In addition, design for hot carrier reliability approach [4-6] was incorporated into the op-amp design. The design rules were developed by a) performing the hot carrier aging tests on both SOI n- and p-MOSFETs with multiple channel lengths and widths at various temperatures down to -160ºC; b) correlating the op-amp performance requirements with transistor parameters and thus defining 10% g_{max} degradation as the failure criterion from the op-amp and assembly performance point of view; c) deriving the thermal profile of the op-amp based on its power dissipation and the environmental temperature profile of the assembly.

2.2 Assembly

The assembly was designed into a double-sided, high density board incorporating chip-on-board (COB) packaging technology. For survival in this cold temperature and high fatigue environment, typical packaging materials and part finishes for commercial applications, e.g. tin-lead alloys, can't be used; meanwhile, the manufacturing processes, e.g. die bonding and heavy aluminum wire bonding, have to be investigated and re-defined.

A set of commercially available material combinations with different manufacturing processes was selected based on its military and space flight heritage and material properties, and two rounds of experiments with test vehicles were designed, fabricated and tested under thermal cycling of -120°C to +85°C using a full-factorial experimental design and statistically significant sample sizes.

Figure 1-3 shows the results of experiment one on the materials selection for substrate, die attach, encapsulant and coating. The green columns with solid line are for test gone through these cycles without failures, while the red columns with dashed line are for test gone through the cycles with failures. Experiment one indicated that polyimide and LTCC substrates with each of the three die attach materials and Parylene C yield the most promising results for the wide temperature survivability.

Experiment two was then designed for further investigation for more materials. Based on the results and analyses of the two experiments, the materials for the assembly was recommended, defined and, along with the electronics, infused into the flight project. Due to the page limit, more details will be provided in the full paper.

3. Technology and Space Qualification

Followed by design for reliability approach during the technology and assembly development and infusion, an application-specific qualification methodology, treating the assembly as a hybrid, was developed to qualify the assembly under the specific space radiation and wide temperature environments, i.e., 6 krad total dose over the mission life and an estimated 670 thermal cycles of -128°C to +20°C environmental on Mars.

The Mars environment temperature is -128°C to 20°C. Adding the estimated thermal dissipation during the mission and thermal margin during qualification, the qualification temperature was determined as -143°C to 125°C for electronics, and -120°C to 85°C for packaging and assembly.

Since the technology infusion was planned during the initial phase of the op-amp design and development, the technology qualification and the space qualification for the op-amp were integrated together. The qualification baseline is MIL-PRF-38535, but with additional qualification steps to address the lower temperature operation, which includes screening and life test at low temperature. Known good die (KGD) approach was also integrated into the op-amp design and qualification. Total Ionizing Dose (TID) and Single Event Transient (SET) tests were performed at the room temperature, not at low temperature because of the annealing effect and the varying operating temperature condition.

In addition, for all critical electronics on the assembly, the element evaluation and large sample characterization were added and conducted. This qualification step was determined and defined from MIL-PRF-38534, treating the assembly as a hybrid. Both element evaluation and large sample characterization were performed at temperatures of -143°C, -55°C, 25°C and 85°C, which were critical to the worst case analysis on the assembly. Figure 4 is shown as one example.

At the assembly level, the space qualification had a few more steps, which included a qualification process for the packaging material combinations to demonstrate a survivability of at least 3x of the mission targeted life time, i.e. over 2010 thermal cycles of -120°C to 85°C, assembly level thermal cycling with electronics and packaging materials, and a final planetary protection test.

Obviously, a high level of reliability was required for this application, but all the electronics and materials were not designed for the environment. This challenge called for an application-specific qualification approach at an optimized combination of component level and assembly level qualification processes. Details will be provided in the full paper.

4. Summary

This paper describes the details for the qualification of a motor drive electronics assembly for Mars Curiosity Rover under space extreme environments.

Table 1: Slew rate and bandwidth temperature dependence of 85ºC to -140ºC for the three bias techniques

	Constant *I*	Constant *gm*	Constant *IC*
SR Variation (SR_{85}/SR_{-140})	1	W.I.:2.7 S.I.: 4.4	1.64
BW Variation (BW_{85}/BW_{-140})	W.I.: 0.37 S.I.: 0.48	1	0.609

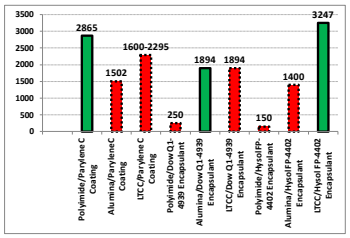

Figure 1. Number of Cycles with Ablebond 967-1 Si die attach as a function of Substrate and Coating/Encapsulant.

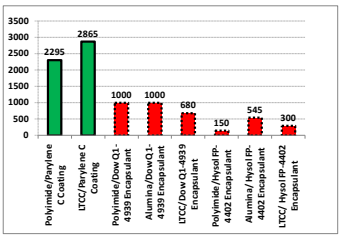

Figure 2. Number of Cycles with Pure Indium Si die attach as a function of Substrate and Coating/Encapsulant.

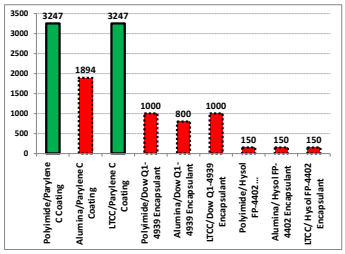

Figure 3. Number of Cycles with Zymet TC-611 Si die attach as a function of Substrate and Coating/Encapsulant.

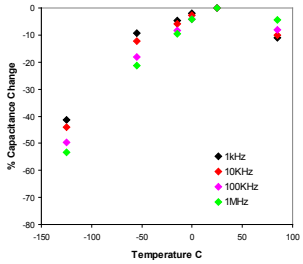

Figure 4. Representative capacitance percentage change as a function of temperature and frequency for a ceramic capacitor.

5. References

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