

Report of the Odyssey FPGA Independent Assessment Team

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Abstract: An independent assessment team (IAT) was formed and met on April 2, 2001, at Lockheed Martin in Denver, Colorado, to aid in understanding a technical issue for the Mars Odyssey spacecraft scheduled for launch on April 7, 2001. An RP1280A field-programmable gate array (FPGA) from a lot of parts common to the SIRTf, Odyssey, and Genesis missions had failed on a SIRTf printed circuit board. A second FPGA from an earlier Odyssey circuit board was also known to have failed and was also included in the analysis by the IAT. Observations indicated an abnormally high failure rate for flight RP1280A devices (the first flight lot produced using this flow) at Lockheed Martin and the causes of these failures were not determined. Standard failure analysis techniques were applied to these parts; however, additional diagnostic techniques unique for devices of this class were not used, and the parts were prematurely submitted to a destructive physical analysis, making a determination of the root cause of failure difficult. Any of several potential failure scenarios may have caused these failures, including electrostatic discharge, electrical overstress, manufacturing defects, board design errors, board manufacturing errors, FPGA design errors, or programmer errors. Several of these mechanisms would have relatively benign consequences for disposition of the parts currently installed on boards in the Odyssey spacecraft if established as the root cause of failure. However, other potential failure mechanisms could have more dire consequences. As there is no simple way to determine the likely failure mechanisms with reasonable confidence before Odyssey launch, it is not possible for the IAT to recommend a disposition for the other parts on boards in the Odyssey spacecraft based on sound engineering principles.

Introduction

JPL management requested outside expertise to aid in understanding a technical issue for the Mars Odyssey spacecraft scheduled for launch on April 7, 2001. An Independent Assessment Team was formed for this purpose and met on Monday, April 2, 2001 (see Appendix 1 for list of attendees) to hear presentations relevant to analysis of these failures and to assess the failure investigation and recommend disposition of parts on Odyssey board. In particular, the objectives of the review and analysis were to review the available data, determine if all possible and meaningful actions have been followed, provide expert opinion on the validity of the analysis results, suggest possible failure mechanisms for the FPGA failures, and assess the implications of each possible failure mechanism on FPGAs from Odyssey flight FPGAs. Members of the Independent Assessment Team consisted of Donald Mayer (Chair) and Jon Osborn both of The Aerospace Corporation, Rich Katz of NASA Goddard Space Flight Center, and Jerry Soden of Sandia National Laboratories.

An RP1280A field programmable gate array (FPGA) failed on a SIRTf printed circuit board. This device was from a parts lot designated U1H466 common to the SIRTf, Odyssey, and Genesis missions. The RP1280A consists of a commercial 1.0 μm Matsushita A1280A die packaged by Space Electronics Inc. (SEI) using their package shielding technology and electrically tested, screened, and procured through Actel. This may provide higher levels of total dose radiation tolerance than the A1280A or RT1280A, which use the same dice with normal Actel packaging. An alternative pin-compatible device is the RH1280 that is produced on Lockheed Martin's radiation-hardened/high-reliability processing line in Manassas, Virginia. The RP1280A was chosen by Lockheed Martin (Denver) for cost and heritage reasons and the devices delivered by Actel for the SIRTf, Odyssey, and Genesis programs were the first lot of devices ever delivered by Actel using the SEI packaging technology.

Prior to the meeting, information made available by Lockheed Martin, JPL, and Actel was carefully reviewed. Lockheed Martin had concluded initially on March 16 that the most probable cause of failure was a particle contaminant but during the IAT meeting stated that the cause of failure was unknown; JPL considered the FPGA failure a random occurrence. Additionally, the material suggested that there had been a second FPGA that had been removed from an Odyssey board due to anomalously high current, and that was found to be the case, and the Problem/Failure Report was provided.

IAT Review Process

The review consisted of presentations by Lockheed Martin and JPL personnel, questions by the IAT participants and other attendees, a part mechanical test, and a lab visit. Schematic drawings of the board and FPGA designs were not provided to the IAT for evaluation prior to or during the meeting despite requests, but were provided the day prior to launch. One outcome of the review was that the particle initially reported as the probable cause of the SIRTf failure was most probably an artifact of Lockheed Martin's processing. JPL also proposed an ESD model for the cause of failure, but was unable to show a physical correlation with the failed flight unit. In summary, the data shows that there are two failed flight RP1280A FPGAs at Lockheed Martin and there is no known cause that can be established for either failure.

The failure analysis methodology and its results were discussed in depth. Various analysis techniques were used which are common to many device types and failure analysis laboratories. However, the features inherent in Actel FPGA technology for internal characterization were not exploited. The device architecture and support hardware and software are capable of a variety of diagnostic and electronic probing tests. These capabilities, when combined with traditional failure analysis techniques, often provide critical information for the analysis of failed devices. Both failed devices were destructively processed in the failure analysis laboratory before information based on Actel-specific non-destructive diagnostics and analyses could be obtained.

Possible Failure Mechanisms

The failure mechanisms for the Odyssey and SIRTf failures are not known, but some speculations may be made from the data presented.

The FPGA failures involved the parts drawing excessive current. At the time the parts were removed, the SIRTf part had failed functionally while the Odyssey part had not. A hot spot was identified in the Odyssey failure. This site (in the core of the device) could have been the source of the high current (22 mA) observed as the failure signature for this part. However, no reproducible individual hot spots were identified in the SIRTf failure that might source the high currents observed, and no single point failure site is known that might allow the very high current levels (more than 500 mA) observed. Therefore, it is likely that the observed leakage current in the SIRTf part is global in nature or distributed over a large number of discrete points. Theoretically, possible failure modes could be failure of one of the charge pumps, which provide the gate voltage to the pass gates that connect logic module inputs and outputs to the programmed interconnects, a conductive short that pulls a net to an intermediate voltage instead of a rail, an open or high-resistance conduction path that allows some critical net to float to intermediate potential, or some other unknown problem.

The lack of sufficient information about the failures precludes identification of the failure mechanism. However, there are a number of potential failure mechanisms that might have created the observed failure mode. Speculation of a few possibilities follows.

ESD/EOS during handling at Lockheed-Martin

If the parts were ESD damaged during handling, for example in the programming, assembly, stocking, kitting, or test areas, it would likely create a defect that would result in an immediately observable failure or change in part performance. It is also possible that such an event could create latent damage that would worsen with time, such as a metal open or short, or a gate oxide defect.

Likelihood that this proposed mechanism is root cause of Odyssey/SIRTf part failures - Unknown but probably low. The parts might have been damaged during handling at Lockheed-Martin, in spite of their ESD control procedures. An ESD or EOS event can create damage in an oxide of an integrated circuit that would result in a hot spot during subsequent failure analysis. However, Actel has not observed ESD damage at the location (in the core) identified by Lockheed-Martin; no damage was seen in the I/Os where damage is normally observed. Lockheed-Martin has not observed ESD damage in prior parts handled in their facility in 15 years.

Corrective action, if proven as failure mechanism - Improve ESD protection and awareness at Lockheed-Martin (e.g., conductive floor mats, verify earth grounds, ground test fixtures, add ionizers if necessary, etc.).

Recommendation, if proven as failure mechanism - Requalify or replace all FPGAs potentially exposed to ESD at Lockheed-Martin. Demonstrate reliability of remaining parts by reasonable amount of additional testing, screening, and analysis.

Manufacturing defect (systemic)

An error during manufacturing may have affected all devices on a wafer or in a wafer lot. The wafer ID was not available because the Action Probe was not used in the diagnostics. This might include overetched poly gates, incompletely etched contacts or vias, or inadequate metal step coverage in contacts or vias. If most defects were found, but some escaped, and worsened with time due to time-dependent dielectric breakdown (TDDB) or electromigration, for example, it might generate the observed symptoms.

Likelihood that this proposed mechanism is root cause of Odyssey/SIRTF part failures - Unknown but probably low. A systemic processing error would likely have resulted in out of family behavior for the manufacturing lot, which does not seem to be the case here, considering history of parts from the same wafer lot that were not handled at Lockheed-Martin. However, if manufacturing process was nominal but with variations that allowed significant population with marginal defects, some escapes would be possible, which may explain SIRTF failure. However, based on statistics provided by Actel, that is not characteristic of Actel parts built at Matsushita in the 1.0- μm process. Gradual degradation of contact hole in global net, for example, might result in floating node over time. However, many or most of the contacts are redundant in these parts. Unstable current behavior observed at Lockheed-Martin during slow power up of failed part is consistent with floating node in global net, conceivably caused by gradual opening of minimally conducting contact during operation, or this can be an artifact of the test that is not applicable to the Actel antifuse technology; note that the charge pump must start for this device to be properly operational.

Corrective action, if proven as failure mechanism - Probably none if shown to be failure mechanism in only one part, due to high reliability of Actel product.

Recommendation, if proven as failure mechanism -. If shown to be failure mechanism in only one part, it would allow use of remaining parts as is. If shown to be the failure mechanism of both parts, do not use parts from this wafer lot.

Board design and/or manufacturing error

It is possible that an error in board design may apply input logic high levels before complete power on, creating electrical latchup. Other possibilities include floating Mode, Vpp, Vsv, or Vks pins on device; the Mode pin termination was not physically checked on the board. Also all unused output pins of Act2 are driven low by automated synthesis tools; they should be floated or tied to resistive loads. Failure to do this might cause EOS problems that could worsen with time or with each repetitive operation.

Likelihood that this proposed mechanism is root cause of Odyssey/SIRTF part failures - Unknown but probably low. Grounded inputs may stress buffers during power up. Such a board design error would likely involve high-current stress failure, such as open metal line. Thorough inspection of board schematics would help bound risk for this failure mechanism.

Corrective action, if proven as failure mechanism - Assurance was given that the power up sequence is well controlled at Lockheed-Martin. This should be verified. Board should be checked for proper application of voltage signals during power-up and during operation. Board schematics should be checked for design problems.

Recommendation, if proven as failure mechanism - Correct board design as needed. Replace FPGAs on suspect boards. If shown to be failure mechanism in one part, it would allow use of parts on other boards with different designs as is; other boards with the same design, replace parts as required.

FPGA circuit design error

It is conceivable that some circuit design problem could cause a latent error, perhaps by overstressing some area of the circuit during power up, for example. It is conceivable that some circuit design error, or error introduced by the automated synthesis tools is creating a fault that places strain on the part leading to degradation and failure. An example might be a timing error resulting in a bus conflict, such as a bi-directional pin being driven as an output by the FPGA while a bus driver is also driving the bus. High currents flowing in the outputs during those bus conflicts can cause accelerated damage.

Likelihood that this proposed mechanism is root cause of Odyssey/SIRTF part failures - Unknown but probably low. Design errors or uncertainties have been observed in the Odyssey schematics, such as grounded inputs, logic hazards at flip-flop clocks, parallel counter with high-skew clocks, and possible setup time, hold time, and synchronization errors. There is no direct link from these logic errors to the failure signatures of either part. This failure mechanism is likely to cause damage due to local high current stress in metal line, and would not result in hot spot observed for Odyssey.

Corrective action, if proven as failure mechanism - Measure in laboratory actual data bus timing, and interrupt vector timing, verify that simulation testbench accurately models application. Re-run simulations looking for I/O driver conflicts.

Recommendation, if proven as failure mechanism - Modify design as needed, and replace all affected devices. If shown to be failure mechanism in one part, it would allow use of parts with different design as is.

Manufacturing defect (random)

A random defect such as a conductive or non-conductive particle may have created a short or open in the circuit, which could have generated this problem. The random defect might initially have had no impact because it may have been only partially closed or open, but may have eventually shorted via TDDB, or allowed electromigration-induced open due to high current density through reduced area. To date, Actel testing and analysis have shown that electromigration-induced opens have not been a problem. It is noted that the Actel metal step coverage in these parts is not out of family, but does not meet military standards.

Likelihood that this proposed mechanism is root cause of Odyssey/SIRTF part failures - Unknown but probably low. This failure mechanism is possible even in a well-controlled manufacturing process, because the particle density in even the best fab is not zero. However, it is not likely to occur twice in one lot. Hot spot identified in failed Odyssey part may be result of defect between metal traces; however defect would have to be latent, since part survived burn-in and passed early electrical tests. This reduces likelihood of random defect as cause of Odyssey failure. Random defect might create observed behavior in SIRTF failure if it resulted for example in gradual degradation of charge pump, or in gradual opening of contact to other global net; note that many of the contacts are redundant and these parts are not prone to that failure mode. Not credible as related failure mechanism for two failures.

Corrective action, if proven as failure mechanism - Probably none. This is not a systemic failure mechanism.

Recommendation, if proven as failure mechanism - If shown to be failure mechanism in one part, it would allow use of remaining parts as is. If shown to be the failure mechanism of both parts, do not use parts from this wafer lot.

Programmer error at Lockheed-Martin

If the programmer did not operate properly during programming operations, the part might have been damaged.

Likelihood that this proposed mechanism is root cause of Odyssey/SIRTF part failures - Unknown but probably low. The Lockheed-Martin estimated programming failure rate of 10 percent is abnormally high for A1280A-based Actel FPGAs. On April 3, 2001, an Actel field application engineer ran the calibration test with Lockheed-Martin personnel and no problems were found. Additionally no problems were found during the adapter module test.

Corrective action, if proven as failure mechanism - Repair or replace programming unit.

Recommendation, if proven as failure mechanism - Remove all FPGAs programmed with this programming device from flight units.

ESD/EOS during handling outside Lockheed-Martin

If the parts were ESD damaged during handling at SEI, Actel, or other location, it may have created a latent defect that would worsen with time.

Likelihood that this proposed mechanism is root cause of Odyssey/SIRTF part failures - Unknown but probably low. Lifetest data on similar parts programmed at Actel show no failures. There are no reports of failures of other parts from this wafer lot.

Corrective action, if proven as failure mechanism - improve ESD protection and awareness at facilities outside Lockheed-Martin or find other vendors for each manufacturing step.

Recommendation, if proven as failure mechanism - Perform part screening and analysis as appropriate to determine acceptability of remaining parts. Requalify or replace all FPGAs from this lot.

Key Findings of the IAT

1. Two parts out of 218 from the flight lot have failed on boards at Lockheed Martin despite having in place high-reliability space qualification parts screening and handling processes.
2. Failure analysis at Lockheed-Martin and Actel has not identified root causes of these failures.
3. The failure rate calculated by Actel for the A1280A part type is below 10 FITs based on Actel lifetest data, which is characteristic of a high-reliability part. There is no evidence of a fundamental reliability problem with the Actel A1280A FPGA.
4. The failure rate for parts on boards at Lockheed-Martin is significantly higher than predicted from Actel reliability data and experience. The failure rates at Lockheed-Martin for these RP1280A devices and for the A1280A parts for the Titan program are two orders of magnitude higher than the Actel data predicts.
5. Circuit design errors have been identified in the Odyssey FPGA, but the likelihood that they are the root cause of the failures is believed to be low.
6. Several possible failure mechanisms have been suggested for each failure, but until mechanisms for these failures are identified with high confidence, use of these parts on Lockheed-Martin boards entails an unknown level of risk.

Conclusions

Observations indicate an abnormally high failure rate for flight RP1280A devices (the first flight lot produced using this flow) at Lockheed Martin and the causes of these failures have not been determined. Standard failure analysis techniques were applied to these parts; however, additional diagnostic techniques unique for devices of this class were not used, and the parts were prematurely submitted to a destructive physical analysis, making a determination of the root cause of failure difficult.

Several potential failure mechanisms have been suggested by Lockheed Martin, JPL, and the IAT as discussed above. Several of these mechanisms would have relatively benign consequences for disposition of the parts currently installed on boards in the Odyssey spacecraft if established as the root cause of failure. However, other potential failure mechanisms have more dire consequences. As there is no simple way to determine the likely failure mechanisms with reasonable confidence before Odyssey launch, it is not possible for the IAT to recommend a disposition for the other parts on boards in the Odyssey spacecraft based on sound engineering principles.

Appendix 1 - Attendees

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