

Advancing Reliable High-Temperature Electronics through Compatible Material Interfaces

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Abstract

The need for digital control and observability is continuing to expand into inhospitable environments - engines, energy exploration systems and space exploration. The limited available selection of components to fabricate modules for these high temperature environments, both active and passive, force manufacturers into packaging compromises that limit the performance and reliability of these modules. The lack of selection, as well as ordering requirements, dramatically slows prototyping cycles and the creation of solutions. Production of thermally hardened active and passive components that are designed and fabricated with packaging in mind can extend the operating temperature range of heterogeneously integrated systems. Ozark IC has demonstrated a wire bonding process that shows reliable powered function of a heterogeneously integrated system at 200°C for over 7500 hours. Ozark IC has also tested modules packaged with homogeneous gold metallization that endure powered function at 800°C for 1 to 50 hours, and powered function at 500°C for more than 100 hours. Increasing the availability of newly manufactured semiconductor die and passive components with compatible metallization would enable these high temperature packaging methods to rapidly advance the state of the art for thermally hardened electronics systems. The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

Key words

Heterogeneous Packaging, High Temperature, Reliability Testing, Rapid Prototyping

I. Introduction

Digitization of our world has accelerated over the last decade. Packaging technology is enabling shorter turnaround times and more compact form factors, all heterogeneously integrated into a single system. The promise is all the benefits of systems on chip – but implemented and tested in a fraction of the time and with all the benefits of the optimization of each underlying technology.

The next frontiers of digitization are applications where the circuits cannot escape environmental conditions; whether those conditions are the extreme temperatures/vibrations encountered in a geothermal well, or on a turbine engine. Such extreme environments are commonly found in mission-critical applications, namely where short-range active control and monitoring of key components in harsh operating conditions could enable substantial optimization of the overall system or operation of essential safety functions.

Essentially, thermally hardened electronics can expand digital monitoring and control capabilities into high temperature harsh environments and provide unprecedented feedback from, and visibility to, previously inaccessible engineering problems [1].

To meet the needs of these next frontiers, Ozark Integrated Circuits, Inc. (Ozark IC) developed the XNode® platform of hardened single-board computers with associated ruggedized packaging [2]. Through these platforms, Ozark IC demonstrated the ability to design and fabricate high-temperature circuits for testing and rapid product development, but the lack of suitable high temperature bare die and passive components is a major limitation faced when developing a new module or fabricating existing designs. The lack of variety in, and documentation for, active bare-die components similarly limits which features the modules can support.

A major barrier to entry in the design and construction of a thermally hardened electronic system is the limited selection of materials, especially heterogeneous metal interfaces, that can be integrated into a system and function reliably at elevated temperatures. Even more restrictive is the lack of variety of passives which are properly rated and/or compatibly metallized. Many components are manufactured in legacy technologies. These legacy technologies require complex packaging techniques that compromise high-temperature performance of the assembled module and vastly increase the cost of fabrication. Likewise, passive components are restricted in their metallization. Offering wider selections of active and passive components finished in gold would enable simpler, more reliable high-temperature packaging.

II. Semiconductor Die Packaging and Availability

For the bare die components that are commercially available with appropriate maximum temperature specifications, most are finished with final Aluminum metallization. This aluminum metallization, when packaged with traditional gold bonding (either flip-chip or ball-wedge bonding), fails relatively quickly at temperatures at or above 200°C. There are processes available that increase the thermal performance of the gold bonding systems, but ultimately an aluminum-gold intermetallic compound formation, colloquially known as the “purple plague,” will cause premature package failures [3]. Other failure mechanisms, such as Kirkendall voiding, can also induce failures in systems where the gold-aluminum interface is present.

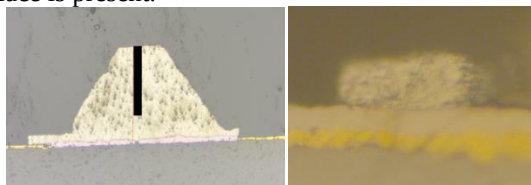


Figure 1: Wire bond exhibiting “purple plague” Al-Au IMCs (left) vs. wire bond with no intermetallic growth after thermal aging at 350°C for 24 hours in a room-air environment (right.)

Ozark IC has developed a method of packaging for these devices using wire bonding that has withstood thermal testing of 24 hours at 350°C in a room-air environment, as shown in Figure 1. However, the packaging process substantially limits other options for system integration including, but not limited to, component attach and substrate fabrication techniques. An alternative wire bonding process, or the ability to utilize gold bond wire, is strongly preferred.

When properly packaged, semiconductor components can last for significant time at temperature. For example, an improved packaging method employed in the fabrication of an AQ200 XNode® enabled continuous powered operation at 200°C for over 7500 hours in a test that is still ongoing.

For high temperature systems, gold-finished components offer a path to tight integration and long-term performance. To emphasize the potential of the homogeneous metal packaging system, Ozark IC packaged gold-finished bare die with superior results when compared to aluminum-gold packaging. This homogeneous gold metal system was tested with both flip-chip and ball-wedge packaging techniques. The active components in this effort were provided by NASA’s Glenn Research Center (GRC) and were fabricated with their V11 JFET-R process. These modules were able to function at 800°C for more than five hours, and substantially longer at 500°C with devices surviving tests more than 100 hours in total duration at 500°C[4].

Figure 2 shows the profile used to test the performance of the GRC JFET-R devices using an all-gold system fabricated in Ozark IC’s facilities.

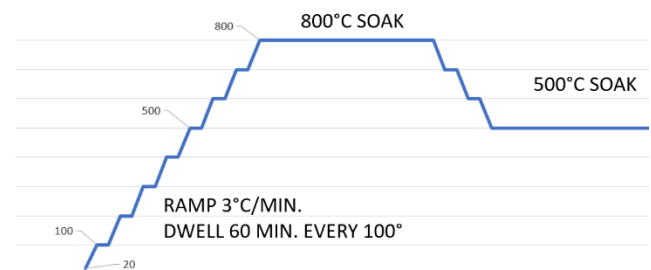


Figure 2: Ozark IC Typical Extreme Temperature Device Testing Profile. 1 Hour Dwell Every 100°C to Verify Device Health Before Continuing Ramp. Not to Scale

Modules with homogeneous metal systems also demonstrated significant resistance to thermal shock, with modules surviving a quench in room temperature water after being heated to 800°C. This testing work demonstrated the potential for thermal soak performance, as well as its resistance to large thermal shocks of more than 50°C per second. Figure 3 shows a module that was quenched in water after heating to 800°C in an oven. The quenched module still functioned well electrically after the quench was complete and the module was allowed to dry. The gold ball bonds used to package this component were partially crushed during the quenching process, as the module landed with the wire bonds facing down into the water quenching container.

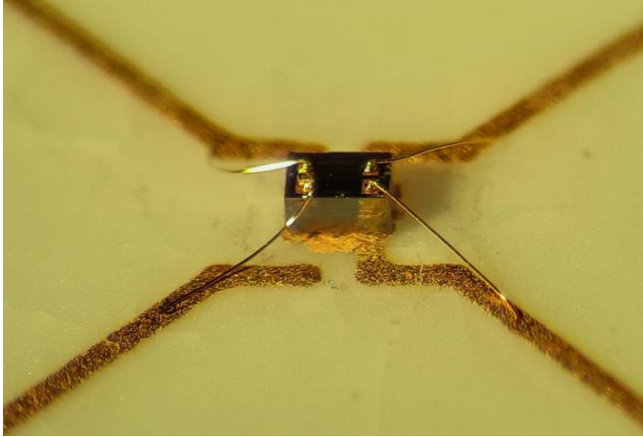


Figure 3: Gold ball bonded die post thermal shock testing and 800°C soaking.

The exceptional performance of these modules is largely attributed to the fabrication techniques that NASA GRC employs in their JFET-R process, as well as the IRIS stack [5] that forms the bond pad structures.

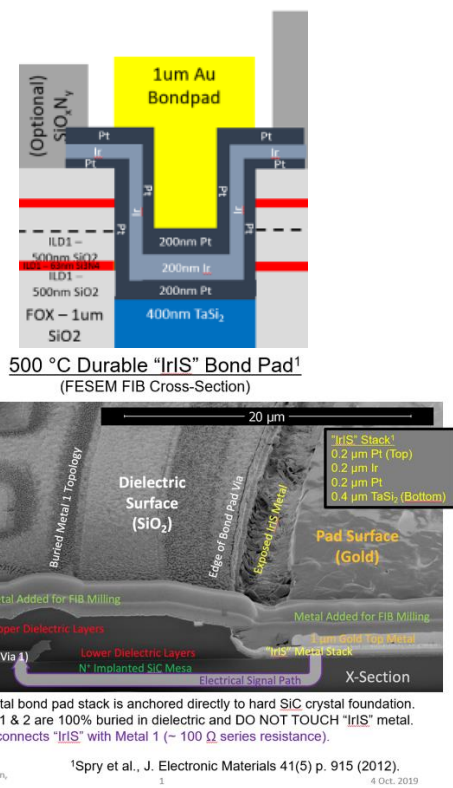


Figure 4: NASA GRC IRIS Pad Metal Stack schematic cross section (top) and SEM image (bottom) [5]

The operating temperature range of existing semiconductor processes can be extended through the improvement of both the packaging process and the component metallization. The integration of gold bond pad structures on the die and higher temperature metallization allows packaging for active

components that is effective at and beyond 350°C for SOI technology.

As the selection of high temperature semiconductors is quite limited, consisting largely of legacy technologies, this represents a gap in the market and an opportunity to bring online new processes with fabrication systems optimized for high temperature performance. Ozark IC currently has several active programs that are addressing this market gap.

III. Passive Component Packaging

Like bare die components, the limited selection and availability of appropriately metallized passive components poses challenges to testing and developing thermally hardened electronics systems. Component selection is driven mainly by models and data provided by active component manufacturers, some of which require further device testing to extend the models to extreme temperatures.

Tin terminated passive components are not suited to high-temperature applications and alternatives are not easily available in quantities that facilitate additively manufactured rapid prototyping techniques. Rapid prototyping methodologies, in general, require a large range of available component values and the ability to order these components in small quantities for evaluation.

Ozark IC has tested many of the commercially available component finishes with various attachment methods and substrate finishes. Samples were tested immediately after fabrication, after aging at 200°C for 100 hours, 250°C for 100 hours, 350°C for 100 hours, and 400°C for 100 hours. Some samples were also thermally cycled to evaluate the component attachment strength after 20 thermal cycles. The profile for thermal cycle testing is given in Figure 5. The samples are cycled from -55°C to 225°C with a ramp rate of 5°C per minute and a dwell time of 15 minutes at 150°C and 225°C.

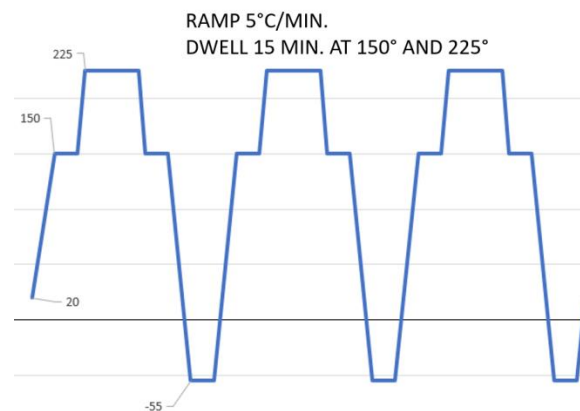


Figure 5: Component Attach Testing Thermal Cycling Profile. Not to Scale

The shear strength of components on modules was tested with a Dage 4000 Force Tester at each stage of thermal aging. In general, the conditions for failure are that the components do not maintain a minimum shear strength of 800gf for a standard 0603 (60 mil x 30 mil) SMD component. Shown in Figure 1Figure 6 is an example of a test substrate fabricated by Ozark IC to carry out the component attach study. 10 samples of each passive were attached to each substrate, and the assembly was subjected to the thermal aging and cycling conditions appropriate to complete the experiment.

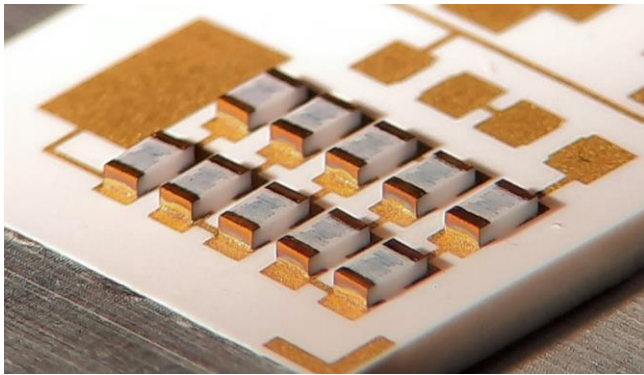


Figure 6: Thin-film SMD resistors after thermal aging, to be sheared for component attach process characterization.

The outcome of these component attach studies may be summarized as; gold-terminated passives were most suitable for high-temperature use out of a large pool of metallized components.

IV. Rapid Prototyping

Ozark Integrated Circuits developed a design and prototyping cycle that employs additive manufacturing techniques to produce single layer interconnects [4]. These interconnect boards are typically designed, fabricated, packaged with active and passive components, and tested in as little as one week. Such rapid prototyping is enabled by Ozark IC's interconnect fabrication techniques and is most frequently bottlenecked by component availability.

A CNC micro dispensing tool, an nScript 3Dn Tabletop, inks traces directly onto a substrate. Without the cost or lead time associated with screens, digital tooling allows progression from design to prototype board in a single workday while achieving 100-micron trace and space where necessary. The low NRE of Ozark IC's method also reduces the cost of design iterations that are often required when characterizing a circuit over large temperature ranges.

Assembly of prototype modules is conducted in stages when practical and appropriate. Passive components are typically

attached first and tested to verify both the attachment and the circuit design before committing the more costly, and often difficult to replace, active components. Attachment methods vary but the method that is both the least costly and lowest risk for a given design is typically selected for prototyping. Selection of attachment method is also driven by the availability of compatibly metallized components. Once a module's passive assembly is verified, then active components are integrated before room temperature active electrical testing and subsequent high temperature testing. Figure 7 depicts a device pad frame on such a module after testing.

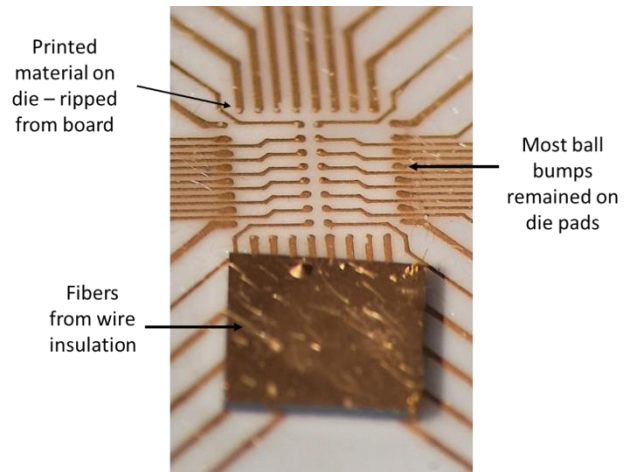


Figure 7: NASA JFET Die Post-test Sheared from an Ozark IC Additively Manufactured Breakout Board

The final step in high temperature packaging is the connector that mates the module with a wiring harness and the outside world. Often an afterthought, an electronics module's reliability is limited to the reliability of the module's connector. Ozark IC opts for the simplest connector solution that has proven robust under laboratory conditions when testing prototype modules up to 800°C. Figure 8 depicts two different iterations of the testing connector.

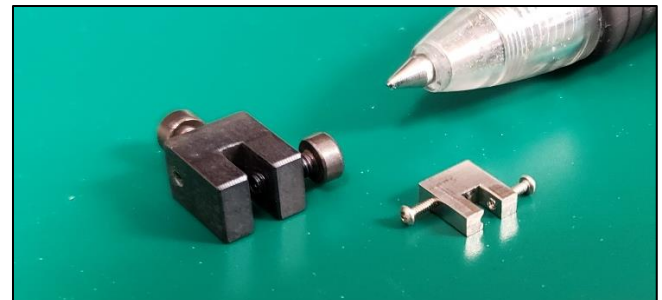


Figure 8: Two Examples of Ozark IC High Temperature Testing Terminals with Pen Tip for Scale

Simple, scalable, single contact terminals secure individual wires to the board and maintain connection for hundreds of

hours at temperatures up to 800°C. For prototypes and characterization modules requiring large numbers of external connections, pin pitches as low as 80 mil are achievable with these screw terminals.

V. Conclusion

Limited availability of both active die and passive components with compatible high-temperature metallization is a major limiting factor for the widespread and reliable implementations of known good heterogeneous packaging methods. Weaknesses in these packaging techniques begin to appear at temperatures as low as 200°C. Ozark IC has demonstrated reliable packaging of homogeneously metallized passive and active components at temperatures of 800°C for tens of hours, and hundreds of hours at 500°C in oxidizing atmospheres. Improved ease of access to appropriate components would also improve the effectiveness of rapid additive manufacturing processes for the generation of IP and modeling data. Successful fabrication of thermally hardened systems requires designing with packaging in mind. Beyond accelerating development of thermally hardened systems, compatibly manufactured components offer the potential for greatly improved temperature and processing performance in heterogeneously integrated systems. The obsolete nature of many of the semiconductor processes for fabricating these bare die components must also be addressed, and new semiconductor processes must be brought online and qualified for the future benefit of high-temperature electronics systems.

Acknowledgment

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA)

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