

Reducing High Temperature System Development Cycle Time and Cost with Additively Manufactured Connectors

Matthew Bakowski, Walter Niblock, Jacob Kupernik, A. Matt Francis
Ozark Integrated Circuits, Inc.
700 W Research Center Blvd
Fayetteville, AR, USA
Ph: 479-935-1600

Email: bakowski@ozarkic.com, niblock@ozarkic.com, kupernik@ozarkic.com, francis@ozarkic.com

Abstract

Connectors are a fundamental part of Ozark IC's high temperature modules from characterization and test packages to Ozark IC's XNode® data acquisition and single-board computing modules. Development of rugged high temperature electronic systems requires the co-development of similarly rugged high temperature connectors. The design and development of connector solutions enable test and evaluation of high temperature systems which would otherwise require fulfillment of a commercial connector order. There is a nascent supply chain of rugged, high temperature-rated connector *designs* but manufacturer lead times for such commercial products can exceed an entire design, prototype, and test cycle. Such delays are incompatible with rapid design iterations and fail-fast strategies employed in the development of extreme environment electronics – especially when the design and test cycles can change the requirements or specifications of the connectors.

Polymer and ceramic additive manufacturing techniques enable in-house connector fabrication and support a connector co-development cycle that complements the pace and interdependent requirements of high temperature system development. These solutions are simple and reliable under laboratory conditions, operating for thousands of hours at 200 °C [1] and hundreds of hours at 800 °C [2]. The use of proprietary connectors manufactured with additive techniques and digital tooling lends an extra degree of freedom to system design and enables the trade-off of connector with system design specifications that greatly accelerates system ruggedization.

Electrical connectors represent the final interface between an electronics module and the outside world. A failure of a connector is a failure of packaging that makes the module opaque to the tester and renders the power and robustness of any electronic system moot.

Keywords

high-temperature, packaging, connectors, additive manufacturing, digital tooling, prototyping

I. INTRODUCTION

Ozark IC's need for high temperature connectors grew out of the need for high temperature device packaging. Naturally, a high temperature device without high temperature packaging is an academic pursuit, as is a high-temperature package without a high-temperature connector to provide the final transition from package to the outside world. During development and testing of Ozark IC's first high temperature

devices, the need for compatible device packaging and a means for signals to escape without confounding packaging failures with device failures became patently obvious.

Pioneers in high-reliability packaging of semiconductor components in the automotive industry were focused on self-heating effects approaching 200 °C at the device packaging level and were not ready to address ambient temperatures above 200 °C [3]. Ozark IC originally solved this 200 °C+

packaging and connector problem in an ad-hoc manner with commercially available off-the-shelf (COTS) ceramic dual in-line packages (DIPs) and threaded fasteners from a local hardware store, as photographed in Figure 1 [4].



Figure 1: Ad-hoc High-temperature Test Package for SiC CMOS ICs circa 2015 [4]

Ozark IC continued development of in-house packaging capabilities and now operates ceramic fabrication, device packaging, and board assembly lines, all in support of continuing the same fail-fast development loop of transparently packaged, rugged electronics systems. Without improved industry support for prototyping, Ozark IC will likely respond in a similar manner to the availability of high temperature packaging – with a vertically integrated supply chain that is linked by in-house manufacturing capabilities to include sophisticated electrical connector components.

II. DEVELOPMENT PACE AND THE FAIL-FAST LOOP

Ozark IC is working to internally standardize several aspects of an integrated electronics system's design to allow development of long-term packaging and connector solutions. However, persistent struggles with a supply chain that include availability, minimum order quantities (MOQ), and the obsolescence of critical active and passive electronic components make Ozark IC's 'standard electronics module's bill of materials a moving target. These constant changes to the electronics along with evolving customer specifications necessitated near total vertical integration of packaging at Ozark IC. Possessing the ability to design, fabricate, and assemble many major components of an electronics module gives Ozark IC the agility necessary to cope with constant system design changes and the freedom to execute fail-fast development strategies. The same need for rapid design adaptation forced connector fabrication in-house as well.

Rather than tooling up injection molding and metal forming machines, Ozark IC's approach to rapid prototyping of

connectors leans heavily on additive manufacturing and low volume CNC machining to supplement COTS components. 3D printable high temperature resins continue to support low temperature (200-250 °C) systems while 3D printable ceramics supported development of high density, high temperature (500-800 °C) demonstration systems. Continued demand for design agility keeps 3D printed connector components relevant at Ozark IC but the rapid increase in requirements for lifetime, I/O density, thermal shock hardness, and demands for enclosure hermeticity are straining Ozark IC's ability to produce connectors that meet system requirements.

III. TRANSPARENCY IN ELECTRONICS PACKAGING: THE WIRE-TO-BOARD PROBLEM

Lessons learned in early device testing work by Ozark IC demonstrated the need for parametrically transparent packaging – the need to reliably monitor the devices and circuits under test whilst remaining reasonably free from the confounding influence of unreliable packaging. That is, for an electronics reliability demonstration, the electronic components must be the first point of failure and not the packaging or connectors. Many early device testing trials suffered from uncertainties introduced by crude and unreliable high temperature [5]. Once Ozark IC's high temperature packaging developed the required level of transparency, the problem immediately shifted to the connectors.

Electrical connectors in Ozark IC's systems typically fill one of two roles: connecting wires together or escaping signals from ceramic wiring boards (CWBs). Generally, wire-to-wire connections are made in the room temperature (RT) domain and many options from the glut of COTS RT connectors are suitable. Wire-to-board connections must occur in the system's operating environment, however, and must reliably endure the same temperature extremes without rendering the electronics system under test opaque to the tester.

The card edge connector was a natural first choice for escaping signals from Ozark IC's high temperature single board computers, but COTS options rated for 200 °C were difficult to find and the few options Ozark IC did identify were either cost prohibitive or the lead times entirely exceeded the related projects' periods of performance – sometimes both. Figure 2 depicts two examples of Ozark IC's in-house solutions for 200 °C card edge connectors.

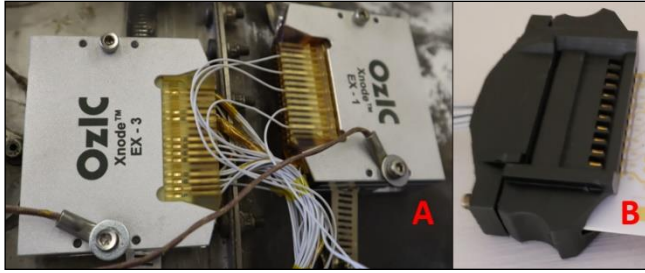


Figure 2: OzIC 3D Printed Resin Edge Connectors. 34 Pin Installed in Field Testing Modules (a), 20 Pin Following Temperature Soak Test (b)

While both designs pictured above were successful insofar as they enabled program progression, Ozark IC's 3D printed edge connectors suffered from significant drawbacks related to both the 3D printable resin (described in Section IV) and the performance of the available COTS spring contacts. System test and iteration were greatly frustrated and slowed by intermittent and poor connectivity that were initially misidentified as circuit issues.

Ultimately, the connectivity issues were caused by the spring contacts employed by the edge connectors. Contacts made from a traditional electronics spring alloy were selected in part for their ubiquity and simply because no contacts in more suitable alloys were readily available. While the contacts made of common spring alloys have improved resistance to stress relaxation over some other traditional electrical contact alloys, they do not sufficiently resist stress relaxation to endure more than a few hours of 200 °C service when compressed to a working load. Indeed, with improvements to the connector design, the same spring contacts that proved unreliable remained connected for thousands of hours of temperature soak at 200 °C under laboratory conditions but only until perturbed (e.g., thermally cycled); at which point the contacts immediately failed.

Following Ozark IC's acquisition of eutectic solder reflow capability, soldering contacts directly to CWBs became the preferred option for 200-250 °C systems. Individual contacts were preferred over lead frames to ensure forward compatibility as designs evolved but the selection of contacts was also frustrated by commercial availability. Soldering of SMD contacts, Ozark IC's preferred method, to a CWB typically resulted in substrate failure during the reflow cycle. The lack of readily available contacts made from controlled expansion alloys or other alloys with sufficiently matched coefficients of thermal expansion prevented further development. Ozark IC opted for crimp-on pin and socket contacts, instead soldering short wires of a more appropriate alloy to the CWB, as depicted in Figure 3.



Figure 3: Wires with Pin Contacts Soldered to a Ceramic Wiring Board and Seated in a 3D Printed Isolator Block

While electrically successful, the wire and pin may act as a lever against the solder joint demanding rigid strain relief to avoid damaging the CWB. Concurrently, the need to escape signals from CWBs at temperatures in the 500-800 °C range for device testing resulted in an entirely different set of solutions.

The most reliable and electrically transparent connector system Ozark IC tested over any temperature range under laboratory conditions is the Single I/O connector (see Figure 4).

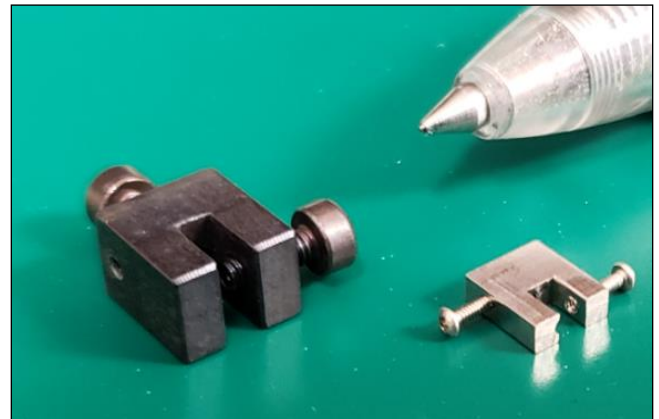


Figure 4: Examples of Single I/O Connectors, 800 °C 0.250" Pitch (black), and 350 °C 0.080" Pitch (silver), Pen Tip for Scale

A simple C-clamp, the Single I/O connector is nothing more than a crude spring. Made from materials more resistant to stress relaxation than alloys of the COTS spring contacts, the Single I/O connectors remain clamped securely to their CWBs. These simple connectors not only survive thousands of hours at 500 °C and hundreds of hours at 800 °C but also endure thermal cycles and are suitable for reuse.

Despite their simple ruggedness in the laboratory, their bulk and high assembly effort makes Single I/O connectors generally unsuitable for field applications, but the Single I/O remains the connector of choice for Ozark IC's device testing and characterization services.

IV. HIGH TEMP. ELECTRICAL ISOLATION

The next challenge in high temperature connector development is the selection of suitable dielectric materials for electrical isolation of adjacent signals. There exists a wealth of dielectric materials serviceable up to 350 °C but the need to produce custom parts quickly in-house or in small quantities through external services narrows the selections significantly. Without specialized equipment, or significant investment, many dielectrics are not practical.

Ozark IC's original high-density 200 °C solution relied solely upon 3D printed high temperature resins. Edge connectors were fabricated completely from 3D printable resin for reasons of simplicity and in-house manufacturability. 3D printing also enables greater design freedom than some traditional manufacturing methods and the digital nature of tooling significantly reduces the cost of prototyping iterations.

The parts made from 3D printable resin demonstrated adequate service lifetimes at 200 °C in laboratory conditions but nonuniform thermal environments of some real-world applications testing ended with parts failures. Ozark IC currently attributes these failures to the thermal properties and thermal aging characteristics of the resin (see Figure 5).



Figure 5: 3D Printed Resin Edge Connector Post-Exposure to a Large Thermal Gradient. Cold side (a), Hot Side (b) with Crack Indicated

Some of the resin's drawbacks were avoided in subsequent designs by utilizing smaller, simpler parts that are largely non-structural – serving only to isolate adjacent conductors from one another and relying upon metal components for strength. 3D printed high temperature resins remain a viable option for many connector components at Ozark IC and process development aimed at improving performance of the parts continues.

For very low-density connections, particularly when conducting testing under laboratory conditions in the 500-800 °C range, an air gap is sufficient. Ozark IC eases the I/O density burden for such tests simply by increasing fan out, as depicted by Figure 6.

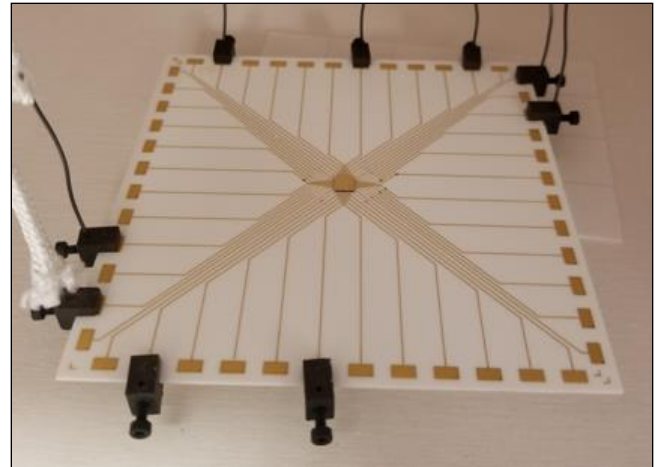


Figure 6: Example of a Full Device Breakout Designed for OzIC 800 °C Single I/O Connectors

When connection density requirements demand a contact spacing where adjacency shorting is a risk, ceramics are the only practical option for the 500-800 °C range. Fortunately, 3D printable ceramic filled resins are also available.

While the finished parts for the prototypes performed adequately, achieving the best results from the 3D printable ceramics typically requires special equipment – a hurdle Ozark IC was able to overcome on small parts with careful process control. Ensuring complete debinding and repeatable vitrification of the green parts also demanded careful adherence to design rules that limited possibilities for the ceramic parts. Figure 7 depicts examples of such 3D printed ceramic parts.

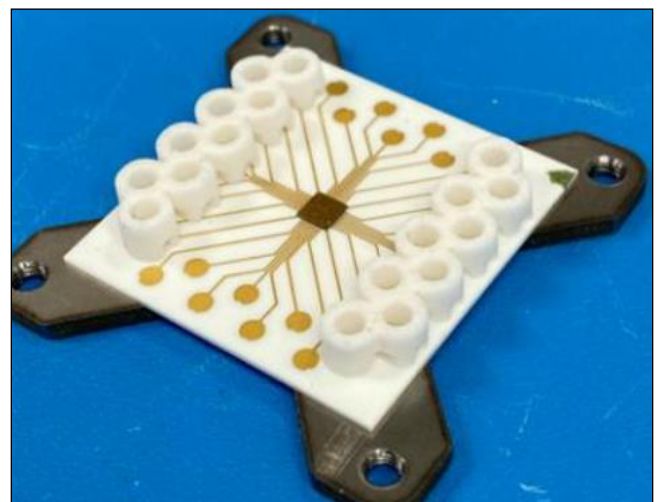


Figure 7: 3D Printed Ceramic Isolators for OzIC Prototype High Density 500 °C Connector, Pictured with Packaged Device

Despite the difficulty of maintaining a reliable process without specialized printers, 3D printable ceramics offer undeniable benefits to systems in the 500 °C and above temperature

regimes for improving connection density. Ozark IC plans to continue development of high temperature connectors employing 3D printed ceramics in the absence of suitable alternatives.

V. ADVANTAGE OF ADDITIVE MANUFACTURING WITH DIGITAL TOOLING

Additive manufacturing techniques offer certain advantages over their more traditional subtractive counterparts, especially for designs that benefit from complicated internal features – such as electrical connectors. Additive manufacturing alone does not reduce prototype cycle time and non-recurring engineering (NRE) costs alone. The main factor in reducing costs of prototype cycles at Ozark IC is digital tooling.

Manufacturing processes that employ digital tooling over physical tooling (i.e., screens, masks, molds, die, etc.) offer a direct path from design to finished parts without the intermediate step of producing design-specific tools to support a process. Iterating prototype designs without digital tooling can incur NRE that slows down the fail-fast cycle and accrues tool sets that may not be useful to subsequent iterations. Digital tooling not only eliminates the NRE of design-specific tooling but also affords greater freedom to change designs from iteration to iteration without the pressure to reuse expensive, preexisting tooling.

Digital tooling paired with additive manufacturing techniques also offers a shorter, less expensive path toward prototyping with design specific tooling. At Ozark IC, the cost of tooling up for operations such as casting and forming is reduced through 3D printing of tools. Ozark IC has begun to explore the possibilities of leveraging homemade tooling for the creation of complex parts via more traditional manufacturing techniques.

VI. CONCLUSIONS

Maintaining parametric transparency of the active electronics through electrical connectors and electronics packaging systems is critical to validating new systems quickly. Co-development of packaging and connectors alongside electronics are decelerating but, ultimately, necessary parts of doing business in an ecosystem that is generally unfriendly to prototyping and low volume production. Further, expansion of in-house capabilities to manufacture connector components is essential to sustaining the fail-fast development model that Ozark IC employs. Inability to source key components quickly and economically is not simply decelerating; lead times and costs of some parts are program-killing in the absence of an alternative.

In-house manufacturing of connector components to supplement suitable COTS parts is instrumental to

maintaining transparency of packaging without disrupting the fail-fast system development loop. Additive manufacturing of connector components using digital tooling enabled, and will continue to support, much of Ozark IC's work in extreme environment electronics.

VII. ACKNOWLEDGEMENTS

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