Packaging Design & Manufacture of High Temperature Electronics Module for 225ºC Applications utilizing Hybrid Microelectronics Technology

Jacob M. Li
Vectron International
267 Lowell Road
Hudson, NH, 03051
Tel 603-598-0070, jli@vectron.com

Abstract

Many downhole instrumentation tools manufacture today utilizing organic material packaging technology for producing electronic modules. Such approach with organic PCB, standard packaged discrete semiconductor and SMT-type passive components has limited the device operating temperature range in 177ºC area. An alternative packaging approach is to utilize Hybrid Microelectronics Technology to increase the operating temperature limit up to 225ºC in production environment. Besides performance improvements on upper operating temperature limit, thermal cycling, high frequency shock and vibration, based on our customer's reliability testing data, hermetically sealed high-temperature Hybrid module's survivability can exceed over 7000 hours of MTTF at 225ºC high temperature storage condition along with other environmental matrix testing. Moreover, comparing with high-temperature SMT and Thru-hole Technologies, Hybrid Microcircuit increases packaging density and provides valuable real estate saving. Vectron International has successfully utilized Hybrid Technology to manufacture thousands of hi-temperature electronic module for 200ºC to 225ºC applications. This paper describes the packaging design of a 225ºC hi-temp electronic module for down-hole application using such technology. This paper will also touch bases on material selection, fabrication technique and some reliability data of this high-temperature Hybrid module.

Key Words: High Temperature Electronics, Hermetic Seal, Thick-Film

Introduction

Extreme environment applications require electronic system survived beyond the familiarized MIL-STD operating temperature range of -55°C to +125°C. Applications such as Deep Well Logging Tools (sensor, gauge and data acquisition etc.), Geothermal Logging, Light Weight Ground and Air Vehicles and Industrial Process Monitoring require robust electronic system that can operate at 200°C and beyond. In addition, some of these applications also require survivability under high shock and vibration environments. Market drivers such as Fuel Consumption needs for Transportation and Electronics needs for Automotive, Commercial and Military Aircrafts are continuously expanding. Although the present market for high-temperature electronics is small and has been dominated by the petroleum well-logging industry, but it could develop tremendously if the automotive market opens up. Aerospace is another area that show promise for the near term [1]. The benefits of deploying high-temperature electronics, to say the least, include: 1) Eliminating needs of auxiliary cooling with massive heat sink or heat pipe design; 2) Lighter Weight and Smaller Size and 3) Integrating sensors and other transducers directly at the crucial location of interest. In this paper, we will address the manufacturing experience of the high-temperature electronic module for Well Logging Tool application. We will also discuss our packaging design approaches for this specific application. Finally, some reliability data of the Hybrid module provided by our customer, Quartzdyne Inc. will be discussed.

High Temperature Electronic Module

During the past four years, Vectron International has teamed up with another Dover Company, Quartzdyne Inc. to develop the new generation Downhole Pressure Gauge for 225°C application utilizing Hybrid Microelectronics Technology. Requirement from Quartzdyne Inc. is to develop a robust electronics module that can operate continuously at 200°C and is capable of accelerate testing to 225°C. In addition, the electronic module must withstand high impact shock and vibration to simulate the actual downhole drilling environment. Based on such design requirements, our electronic modules have been routinely tested under high-temperature storage, temperature cycling and large repetitions of 1-meter free-fall drop tests to provide quality assurance. Due to its robust performance, the Hybrid microcircuit module has been integrated into the Quartz Pressure Gauge and these pressure gauges have been deployed in the oil field for “Logging while Drilling” and “Permanent Logging” applications. Figure 1 illustrates the high-temperature electronic module in production since year 2000.

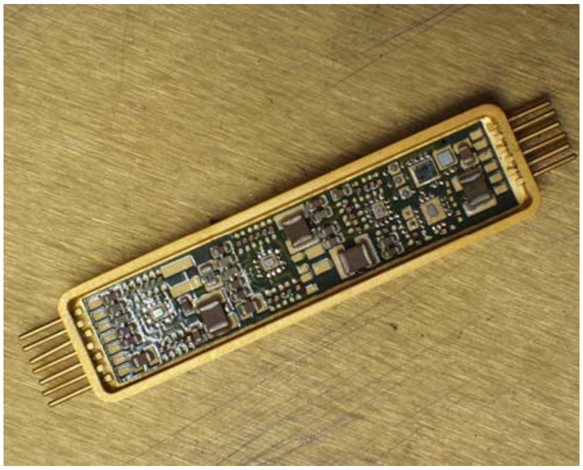


Figure 1: High Temperature Electronics Module

In addition to the unique Quartzdyne Life/Cycle test requirement per each production batch, each individual module is subjected to a 100% screening requirement. Screening test scheme includes: 1) 15 temperature cycles from 25°C to 225°C, 2) 125 hours of 225°C burn-in storage and 3) 10 1-meter free-fall drops to steel plate. Quartzdyne has estimated the impact of the 1-meter free-fall drop to be approximately 1 million g’s in a microsecond based on extrapolation of data measured at lower impacts [2]. During the past 4 years, Vectron International has produced over 3000 Hybrid high-temperature modules.

Packaging Design Approaches

To meet the challenges, the high-temperature electronic module has been designed with the following approaches:

- Replace High Temperature PCB with inorganic ceramic substrate material
- Use multi-layer Thick-Film Fabrication technique to increase packaging density
- Select crystalizable Dielectric composition to provide reliable insulation between inner conductor layers
- Seal custom metal package hermetically to protect electronic circuit mechanically and away from corrosive, humid environment
- Use Pd-doped Au Thick-Film composition to provide reliable conductor surface for both Au and Al wirebonds
- Use High Tg thermoplastic adhesive material to provide reliable Substrate-to-Metal Package attachment
- Up-screen and select components meticulously

Multi-Layer Thick-Film Substrate

96% Al_2O_3 material is selected as the base substrate material for this application. Al_2O_3 substrate provides better CTE matching with MLC chip capacitor and alumina-based Thin-Film and Thick-Film resistors. The module’s substrate has a total of 5 metal layers and 181 vias for interconnecting all conductor layers. The entire fabrication process includes 23 screening sequences. A filled and crystalizable Dielectric composition is used for providing excellent insulating property between conductor layers. The Dielectric material also offers outstanding CTE matching with the base substrate. With proper process control and fabrication procedure, the Dielectric material provides exceptionally smooth surface condition for robust wirebonding. The overall dimension of the Multi-Layer Thick-Film substrate is 45.72mm(1.800") L x 9.65mm(0.380") W x 0.635mm(0.025") T.

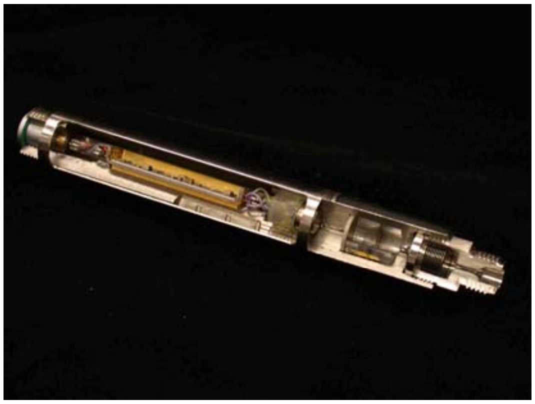


Figure 2: Cross-section view of Quartzdyne Pressure Gage Tool

Finally, the Multi-Layer Thick-Film substrate has increased the overall packaging density and it has contributed to the size reduction of the Quartz Pressure gauge from 1" OD to 0.75" OD as shown in Figure 2.

Hermetic Sealing with Metal Package

Hermetic sealing provides protection from mechanical damage and intrusion of the atmosphere contaminants. Our high-temperature module consists of: 1) Active Components- IC and Transistor die, 2) Passive Components-Thin-Film NiCr resistors, Thick-Film chip resistors and MLC chip capacitors, 3) Interconnects-Au and Al wirebonds and conductor traces on the ceramic substrate. It is well documented that semiconductor die are quite susceptible to contaminants (such as moisture, airborne particles, and ionic contaminants) and various gases (such as ammonia, sulfur dioxide, carbon dioxide, and hydrogen) [3]. In addition, reduction or elimination of moisture, ionic contaminants and Halogen gas contaminations can improve wirebond reliability and prevent silver migration and oxidation that causes from moisture diffusion to the polymer materials. Besides assembling the high-temperature electronic modules in a Class 10K cleanroom environment with full humidity and temperature control, all modules have gone through stabilization bake process in dry nitrogen and vacuum environment following by seam sealing process inside a dry nitrogen glovebox. After seam sealing, all modules are subjected to 100% Gross Leak and Fine Leak tests in accordance with MIL-STD-883 Method 1014.9.

To ensure mechanical robustness under high shock and vibration environment, the custom metal package is constructed with ASTM F-15 alloy and a reinforcement mounting bar is added underneath the large aspect-ratio flatpack housing as shown in Fig 3.

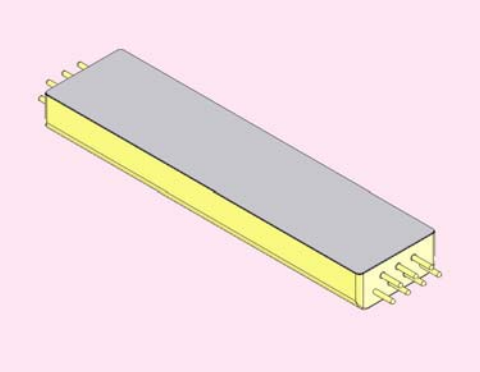


Figure 3: Custom Metal Flatpack

I/O pins are constructed with Glass-to-Metal Match Seal method with 7052 borosilicate type glass material. The CTE of all materials used in the match seal must be closely matched at any given temperature between the ambient temperature and the transformation temperature of the glass to prevent excessive mechanical stress damages during cooling process [4]. Proper metal annealing procedure and Au plating thickness specification are critical for the prevention of base metal diffusion to the plating surface and trapped H_2 releasing.

Wirebonding

Microwelding two dissimilar metals can cause interdiffusion and intermetallic formation. A Pd-doped Au Thick-Film composition is selected to fabricate the Multi-Layer ceramic substrate for reliable Al and Au wirebonding purpose. Pd-doped Au conductor resulted either in a relatively stable Au-Al-Pd ternary compound or a concentration of Pd at the interface that slowed both the Au and Al diffusion and lengthened the life of aluminum wirebonds [5]. Our Hybrid microcircuit consists of 98 Au wirebonds for I/O pin-to-conductor and chip resistor-to-conductor interconnections. On the other hand, there are a total of 75 Al wirebonds in the Hybrid microcircuit to interconnect Si die-to-conductor.

Wire selection is also a key factor to improve thermal cycling fatigue failure of the wirebonds. More importantly, process parameters such as as-fired morphology, conductor thickness and bond deformation can have significant impact on the process outcome. Well bonded wires exhibit very low void concentrations at the fully grown state resulting in stronger, reliable bonds after long durations at elevated temperatures [6]. Figure 4 and Figure 5 illustrate both Au and Al wirebond performance under high-temperature storage conditions.

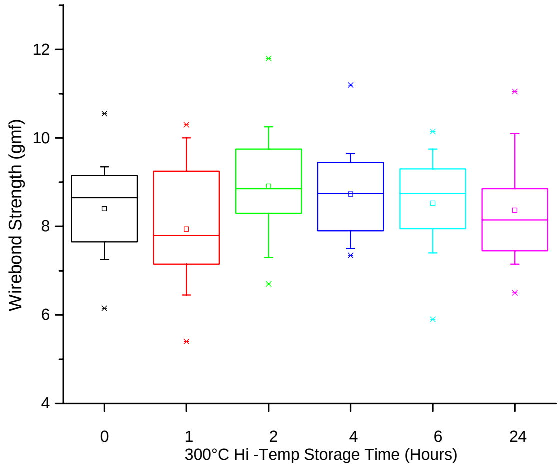


Figure 4: 300°C High Temperature Storage Data of Au Wirebonds on Pd-doped Au

Component and Substrate Attachment

Besides eutectic soldering and adhesive material selections, bond-line thickness of attachment materials and optimized curing or brazing temperature profile are important factor to control void formation, oxidation and outgassing contamination. Void formation can directly degrade component attachment reliability, especially under temperature cycling and high shock and vibration conditions. To improve attachment and electrical performance, eutectic solder was selected to attach sensitive active component as shown in Figure 6.

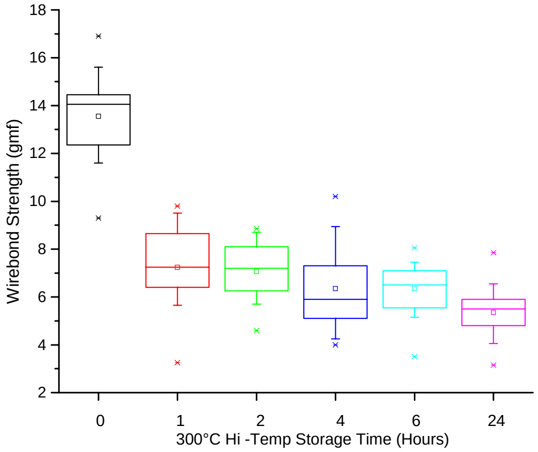


Figure 5: 300°C High Temperature Storage Data of Al Wirebonds on Pd-doped Au

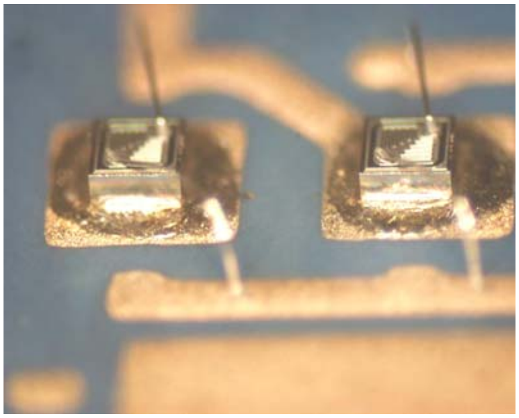
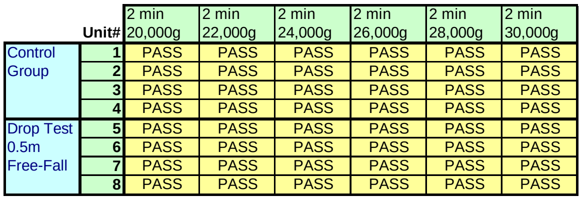


Figure 6: Eutectic Solder Attachment of active devices

High Tg Polyimide adhesive material was selected for the attachment of Si die and other passive components. Another high Tg thermoplastic adhesive material is utilized to attach the Hybrid microcircuit to the metal housing.

Our component and substrate attachment processes have demonstrated exceptional survivability under high shock and vibration, temperature cycling and high-temperature storage environment. Figure 7 tabulates component and substrate attachment reliability data based on 20Kg to 30Kg Constant Acceleration Test on Y1 axis.



	Unit#	2 min 20,000g	2 min 22,000g	2 min 24,000g	2 min 26,000g	2 min 28,000g	2 min 30,000g
Control Group	1	PASS	PASS	PASS	PASS	PASS	PASS
	2	PASS	PASS	PASS	PASS	PASS	PASS
	3	PASS	PASS	PASS	PASS	PASS	PASS
	4	PASS	PASS	PASS	PASS	PASS	PASS
Drop Test 0.5m Free-Fall	5	PASS	PASS	PASS	PASS	PASS	PASS
	6	PASS	PASS	PASS	PASS	PASS	PASS
	7	PASS	PASS	PASS	PASS	PASS	PASS
	8	PASS	PASS	PASS	PASS	PASS	PASS

Figure 7: Constant Acceleration Test Data for 20,000g to 30,000g

Component Selection

Active components of the high temperature module have been up-screened per customer requirement. Device derating design practice and proper thermal management design practice are essential for the overall circuit performance in high temperature. Compact, thermally stable and high energy density capacitors are required for high-temperature application. NPO(K66) MLC chip capacitors are employed in our Hybrid microcircuit because of its excellent TCC and aging characteristics. Regarding the choice of resistor, both Thin-Film NiCr and Thick-Film RuO2 chip resistors are utilized in our microcircuits.

Reliability Data

Reliability data of the high-temperature electronic modules is illustrated in Figure 8. A detail version of the reliability study will be discussed by the “225°C Life Testing of Hybrid Electronic Packaged Circuits for Downhole” paper from Quartzdyne Inc. [2]. Based on the data in Figure 8, our high-temperature Hybrid Module has demonstrated survivability of over 7000 MTTF hours under 225°C Destructive Life/Cycle testing. Due to the success of the Hybrid Module, it has replaced the original Thru-Hole product platform offered by Quartzdyne [2].

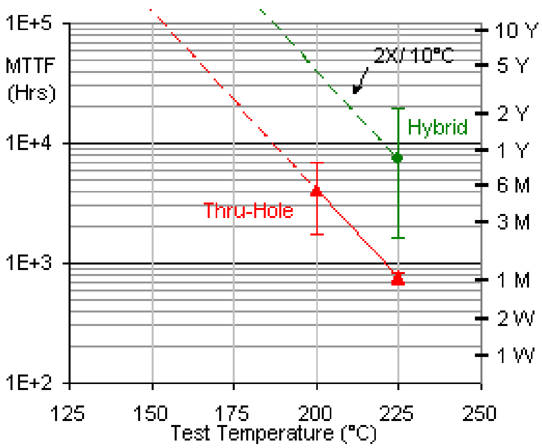


Figure 8: MTTF vs. Test Temperature plot

The continuous improvement efforts between Vectron and Quartzdyne over the past 4 years have come to fruition. We have identified, analyzed and improved our processes to eliminate root cause failures. Improvement areas included Transistor Attachment, MLC Chip Capacitor Attachment, Substrate Attachment and Wirebonding. Our common end goal is to continuously making progress to boost the Hybrid Module’s reliability under actual or simulated field operational environment.

Conclusion

We have successfully demonstrated effective packaging design and manufacturing capability of producing high-temperature electronic module for 225°C downhole application. Based on our 4-year learning curve and the Life/Cycle testing and failure statistics provided by Quartzdyne Inc., we have continuously improved our assembly processes in wirebonding, component and substrate attachment areas. Quartzdyne Life/Cycle Test data has reassured the improvement of the high-temperature Hybrid module with the result of 7362 MTTF hours under 225°C destructive matrix testing conditions [2].

Future High Temperature Electronics Development Topics

Vectron International is committed to expand the high-temperature packaging capability. In near term, Vectron International will continue the effort of developing:

- AlN substrate material for improving thermal management and CTE matching with Si and SiC semiconductor die
- Au-Alloy Brazing Technology for 225°C+ applications
- High-temperature Crystal Oscillator product platform based on Vectron in-house oscillator circuit, quartz and SAW resonator and high-temperature electronics packaging expertise.

Acknowledgements

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Biography

Jacob Li joined Vectron International, a Dover Technology company in August 1987. Presently he is the Director of Manufacturing Technology. Prior to his current position, Jacob has involved in Process Engineering and R&D areas where he has been engaged in the development and invention of new product platforms and technologies for his company. Current development efforts are focused on High Temperature Electronics, Evacuated Miniaturized Crystal Oscillator (EMXO) development and product launching and MEMS sensor technology.

Jacob obtained a BSEE from State University of New York in Buffalo in 1986, a MS Manufacturing System Engineering in 1994 and a MS Management in 1998 from Polytechnic University.

Jacob has coauthored and contributed writing one chapter in “Area Array Packaging Handbook” published by McGraw Hill. His work has been published in several journals and has been awarded two patents. Jacob is a member of IEEE, IMAPS and SMTA.