"Has Microelectronic MCM Technology Matured and is it Capable of Servicing the Widespread Needs of Down Well 225°C Operating Applications in the Oil and Gas Industry?"

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Abstract

This paper reviews development and qualification work performed on 225°C operating temperature modules based on ceramic thick film multi-layer substrates supporting embedded thick film resistors, assembled passive and active components with 'chip and wire' connections and sealing in hermetic metal and ceramic cavity packages. It considers aspects of development and importantly investigates product qualification which includes shock and vibration at elevated temperatures as well as thermal shock and temperature cycling. In conclusion there is an attempt to answer the question "Has microelectronic MCM technology matured and is it capable of servicing the widespread needs of down well 225 °C operating applications in the Oil and Gas industry?"

Introduction

Multi- Chip Electronic Modules (MCMs) or Hybrid Microcircuits have been at the core of API Technologies electronic product range offering for over 40 years. These generic electronic hardware solutions embrace a multitude of package styles and technologies to satisfy a very broad range of circuit functions within system applications. They have a global pedigree with reliability, density and performance as well as an established presence in harsh environments and system critical applications in Aerospace, Space and Defence applications.

It comes as no surprise that these technologies are now being embraced and adopted, albeit cautiously, for the current and next generation Oil and Gas, down well systems including 'Measurement While Drilling' and 'Wireline' requirements and offering new opportunities in geothermal and deeper wells. This technically and commercially demanding industry is adopting a new generation of electronic solutions for sensing, data collection and analysis, to enhance system operation through electro-mechanical control of motors, actuators and valves.

Fundamentally the traditional methods are at the heart of the new ultra high operating temperature (Figure 1) packaging technologies, so it is very much an evolutionary approach that is generally being followed, relying on proven technologies and methods and embracing the industry experiences gained over the past 4 decades (Figure 2). Importantly MCM product development is engineering based throughout the full cycle with close engagement with the original circuit designer so that optimisation can occur at all stages of the design. This theme is an essential ingredient for success with cooperation between electronics, mechanics and material science engineers and technologists each applying their collective skills and experience.

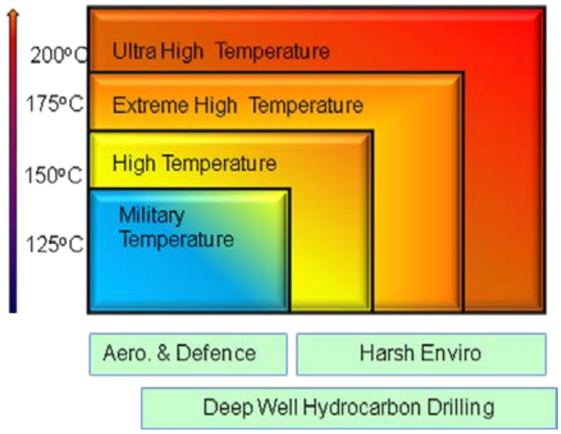

Figure 1 – Classification of temperatures

Circuit Function

A significant percentage of electronics in down hole applications are analogue as they are interfacing to the 'real' world. Functionally the electronics are typically performing sensing, sensor interfacing and associated analogue signal conditioning as well as actuator and motor control. These circuits are usually fed from 'Point-of-Load' DC-DC converters locally located and providing regulated voltages with isolation, current limit and short circuit protection.

The circuit hardware for these analogue functions is a combination of active, semiconductor devices and a broad range of passive components which include resistors, capacitors, inductors and transformers. It is this wide variety of circuit elements that lends itself to hybrid thick film MCM technology but conversely present significant challenges when operating at ultra high temperatures and under mechanical stress conditions.

Key advantages are: reduced electrical connections, closely matched temperature coefficients of expansion of materials, reduced size, improved electrical and thermal performance and hermetic seals providing a controlled environment for the components.

Disadvantages are: large bodied passive components, mixed metal connections, wide ranging component termination metallisations, epoxy and lacquered coated components generating outgassing.

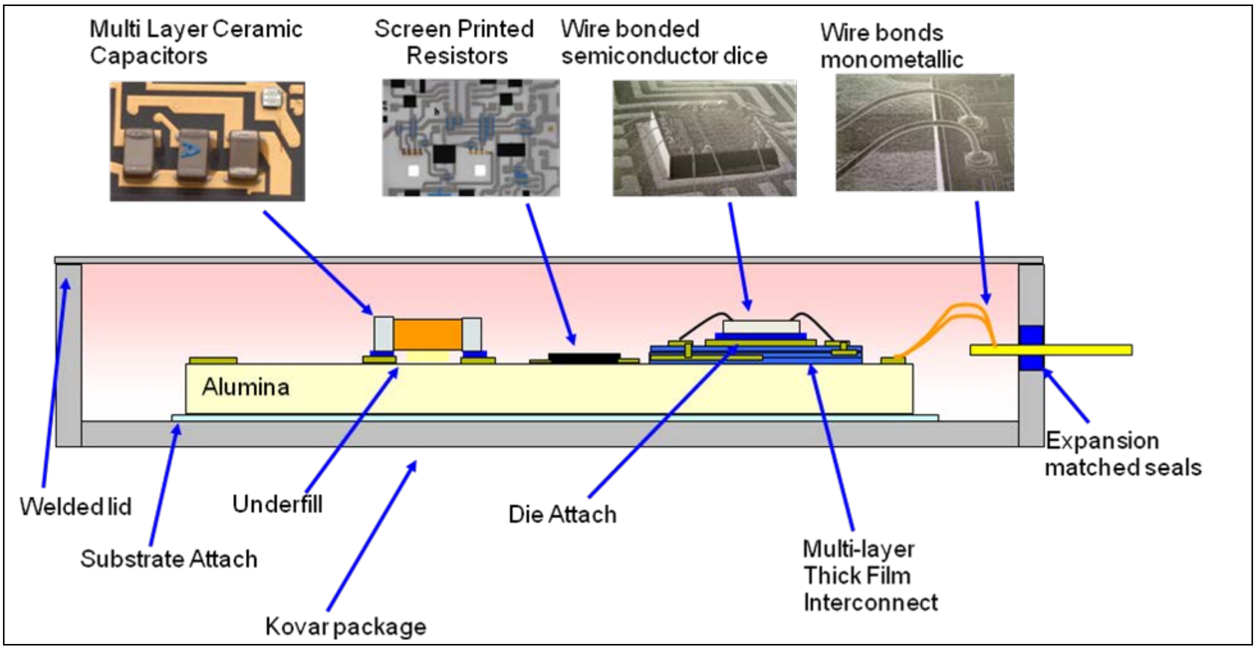

Figure 2 – Typical MCM-C. Multi-Chip Module based on a thick film on ceramic substrate in a welded cavity package

Components

Initially we should consider the availability and suitability of both active semiconductors and passives devices ideally in their unpackaged state. Fortunately there is an established and rapidly growing demand for high operating temperature electronics across many markets and applications. The requirements are seen in automotive in electric vehicles, moves towards all-electric aircraft and in industrial controls.

The fabrication of wideband gap compound semiconductors has transitioned from laboratory scale to volume production with the resolution of the processing problems of the past. In particular silicon carbide (SiC) ,gallium nitride (GaN)and Silicon-on-insulator (SoI) offer exciting characteristics with high switching speeds, low loss, low voltage and high operating temperature. Often the mindset with these components is to minimise heatsinking mass, size and costs and allow them to run at elevated temperature.

Passive components have not seen the radical introduction of new materials that the semiconductor industry has, but there is a new generation of devices that are able to satisfy high temperature needs, but not always ideally suited to MCM-C configurations.

Thick Film on Ceramic Substrate

Thick film printed and fired interconnect on ceramic (96% aluminium oxide Al_2O_3) is a very mature technology with high reliability in harsh environments. Thick film ink systems include conductor and dielectric inks to enable multi-layer interconnections by sequential processing of print-dry-fire. To ensure dielectric integrity these layers are double or triple printed so that pin holes are eliminated and adequate interlayer isolation is achieved. Conductors are precious metals – gold, silver, platinum and palladium and alloys of these metals. Gold with sheet resistivity of around 2 to 3 milliohms is selected as the primary interconnection conductor although silver is an option and the risks of migration mitigated by encapsulation within the hermetic dielectric layers.

The component mounting and electrical connection pads are often through a combination of epoxy, solder, wire bond or weld. These joints dictate the optimum thick film pad material required to ensure a low impedance, reliable connection. Thick film gold is the perfect choice for a good wire bond connection and suited to bridging links on the substrate and for wiring to package Input/Output pins.

Semiconductor die have predominantly aluminium connection pads, so aluminium wedge bonding provides a reliable mono-metallic connection on the die surface. The second bond is usually to the thick film and here alloys of platinum:palladium:gold are essential.

The transition between dissimilar thick film conductors can be problematic with firing temperatures of 850^{0}C to 950 ^{0}C. In particular the repeat firings for subsequent build up of layers, material incompatibility can lead to voiding, blistering, delamination and high resistance contact at the interface.

Thick Film Resistors

Thick film resistors are screen printed, dried and fired onto conductor terminations either directly onto the ceramic tile or on to multilayer structures on dielectric. Compatibility of the resistor inks with the conductor terminations and underlying dielectric is essential. Further firing operations for additional resistivity inks can impact on resistor value, adhesion and stability. Resistors in the range of a few ohms through to 100's kilohms are possible and after ultra high temperature operation, provide end of life absolute tolerances of less than 0.5%. Resistor to resistor matching tolerances can be significantly better than this, enabling tight specifications on such parameters as voltage division and amplifier gain

Package

The hermetic package with insulated electrical feed-throughs provides a robust, hermetically sealed enclosure for the sensitive unencapsulated components – see fig. 9. The package can be seam sealed (Welded), laser welded, glass sealed or soldered to achieve what is classified under MIL-STD-883 Method 104.14 as a hermetic seal. Leaks rates are dependent on package cavity volume but with larger packages, limits are $3x10^{-8}$ atm-cm ^{3}/s He.

Feed-throughs can be with individual matched glass seals or multiple connections with a multi-layer ceramic substrate (HTCC – High Temperature Cofired Ceramic)- see Fig.3.

Figure 3 – Insulated electrical feed-throughs

Qualification

There is no formally acknowledged qualification procedure for microelectronic modules for the Oil and Gas down hole drilling market. However, the internationally accepted MIL-STD-883 standards for Military and Aerospace applications and the British Standards for Environmental Testing together provide a valuable set of controlled methods and procedures that can be applied. Under these guidelines, the qualification of products is divided into sub-groups with typically 3 or 5 pieces and subjected to sequences of environmental stressing with pre, post and intermediate stages of electrical testing to verify functionality.

The tabulation in Figure 5 displays the qualification procedure adopted by API for internal qualification of materials and processes. The testing was performed on the test coupons shown in Figure 6, which covered a range of materials, component types and attach methods with epoxies, solders and welds.

Additional test modules were developed to evaluate multi-layer thick film supporting components and wire bonds and also a range of thick film resistors.

Shock and vibration testing at elevated temperature was performed with custom built 'mini ovens' mounted onto the shock and vibration equipments – see Fig. 4

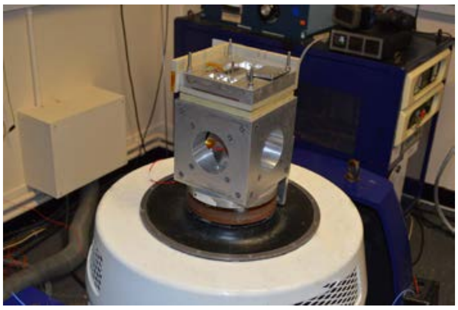

Figure 4 – Vibration testing with module within a compact 'oven' to maintain ultra high temperature

Results

The materials and processes required multiple modifications before an optimum solution was established that successfully passed all test sequences in the qualification plan.

Process control within a tight window is necessary in some cases. For example excessive quantities of epoxy can lead to cracking within the material due to stresses (Figure 5).

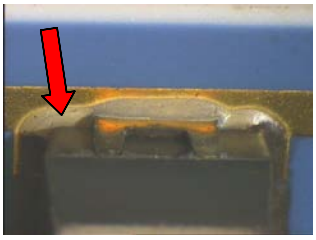

Figure 5 – Epoxy joint exhibiting micro-cracking

The test modules passed all aspects of testing defined in Figure 5 and in particular passed hot storage 230 ^{o}C / 5000 hour endurance but with significant deterioration in epoxy joints. The technology was however established to be very robust after mechanical endurance tests and after 230 ^{o}C / 2000 hour endurance. Wire bonds remained within specification and gold wires on gold thick film were, as expected, particularly strong.

Thick film printed resistors were evaluated on a separate test substrate with 'as fired' values and laser trimmed to value. Resistor drift was measured over 2000 hours at 225 ^{o}C with resistors fired onto the base ceramic and on top of dielectric with values ranging from 100 ohms through to 120 kilohms. All resistor drifts were well within +/-0.5% over this lifetime (Figure 7).

Conclusion

It is ultimately the optimisation of the thick film multi-layer materials for each specific design, the component attachment and the electrical joint technologies that are the biggest overall challenge for ensuring the module integrity and overall long term reliability in down hole applications.

The question being addressed, was ***"Has Microelectronic MCM Technology Matured and is it Capable of Servicing the Widespread Needs of Down Well 225 ^{o}C Operating Applications in the Oil and Gas Industry?"****. In reply, the answer is YES, the technology does exist for the construction of electronic modules suitable for reliable operation at 225 ^{o}C but with the constraint of operating lifetime.*

A wide range interconnection technologies and components including large bodied capacitors and inductors can be accommodated.

It should be noted that it is almost inevitable that some interconnections require organic materials (Epoxies etc) and these will decompose with time at elevated temperature and thus there is a lifetime limit of a few thousand hours depending on the assembly.

Finally, there is essentially a need for engineering expertise in the development of high operating temperature modules to ensure optimisation of the materials, processes and technologies. Ideally all new components, attachments and joints should be evaluated and qualified in their own right prior to incorporation into the module.

Sequence	Test	Condition	No samples	Test Method
1	Temperature Cycle	-40 to 200°C, 100 cycles	2x5	BS9450 ref to BS EN 60068-2-14(Na)
	Visual Inspection	For cracks, delamination		MIL-STD-883H 2017 para 3.1.2 d, g
	Electrical test	Continuity, resistance		n/a
2	Vibration, random	15g rms, 10-1000Hz, 230°C, 30mins	2x5	BS EN 60068-2-64
	Visual Inspection	For cracks, delamination		MIL-STD-883H 2017 para 3.1.2 d, g
	Electrical test	Continuity, resistance		n/a
	Mechanical shock	500g, 100 shocks, Y1 axis, 230°C		BS EN 60068-2-27
	Visual Inspection	For cracks, delamination		MIL-STD-883H 2017 para 3.1.2 d, g
	Electrical test	Continuity, resistance		n/a
3	Hot Storage	230°C, 168h	2x5	BS EN 60068-2-2
	Electrical test	Continuity, resistance		n/a
	Hot Storage	230°C, 500h cum		BS EN 60068-2-2
	Electrical test	Continuity, resistance		n/a
	Hot Storage	230°C, 1000h cum		BS EN 60068-2-2
	Electrical test	Continuity, resistance		n/a
	Hot Storage	230°C, 5000h cum		BS EN 60068-2-2
	Electrical test	Continuity, resistance		n/a

Figure 5 – Qualification Plan

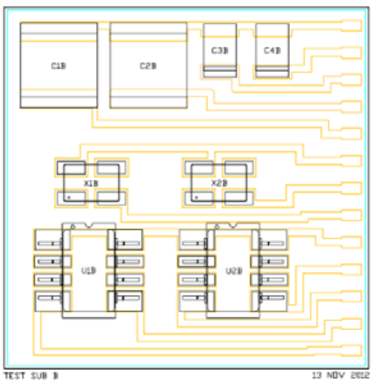

Figure 6: Test Coupon

Resistor thick film ink sheet resistivity	Laser Trimmed to Value	Number of Resistors Measured	Printed on base ceramic or on top of printed dielectric	Range of values	Resistor tolerance drift after 2000 hours at 225 °C. Measured at 20 °C		
					Min	Max	SD
10 Kohms/sq	Untrimmed	96	On Diel.	11K to 120K	0.09	0.17	0.025
10 Kohms/sq	Laser Trimmed	144	On Cer. and Diel.	11K to 120K	0.12	0.37	0.031
1 Kohms/sq	Untrimmed	120	On Diel.	1k to 4K3	0.02	0.05	0.01
1 Kohms/sq	Laser Trimmed	120	On Cer. and Diel.	1k to 4K3	0.04	0.21	0.031
100 ohms/sq	Untrimmed	12	On Diel.	100 ohms	-0.01	0.02	0.06
100 ohms/sq	Laser Trimmed	12	On Cer. and Diel.	100 ohms	0.05	0. 1	0.012

Figure 7 – Resistor stability data

Acknowledgements

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