Lean Process for High Temperature Hybrid Assemblies

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Abstract

Device packaging remains a significant hurdle to implementing electronic systems for high temperature down-hole applications. The demand for higher operating temperatures, combined with recent declines in the high temperature reliability of commercial packages, is forcing the industry to use more ceramic hybrid assemblies. While ceramic hybrid technologies have been developed and proven viable for high temperature use for over 20 years, commercially available processes have been elusive. Most commercial facilities do not take the care required for reliable high temperature operation nor are they scaled for the low volumes typical of the down-hole industry. We present a new hybrid circuit assembly process that has been optimized for high temperature (225°C) hybrid circuits. The process is fully automated and lean, being optimized for small production runs. It is designed for batch sizes from 3 to 12 pieces, with minimal setup change between runs of different designs. Design-for-manufacturability is a key element of the process. Component attach methods include high temperature polyimide, thermoplastic, and eutectic solders. Electrical interconnects utilize both Au and Al wire bonds on either thick-film or co-fired ceramic substrates. The quality of the process is monitored through ongoing life-testing of completed assemblies.

Introduction

Supplying reliable circuits for use in the harsh down-hole environment has always been a challenge. Recent trends in the electronics industry are making it more difficult. The migration of the US military from 125°C rated circuits to commercial parts has decreased the available supply of ceramic-packaged integrated circuits. Reformulation of plastics for finer-pitch commercial packaging has resulted in shorter life times for these parts [1], [2]. At the same time, development of deeper and hotter oil wells and an increased demand for permanently installed electronics have put pressure on down-hole circuit manufacturers to supply more reliable and higher temperature circuits.

As early as 1978, ceramic hybrid circuit technology has been reported to be capable of surviving in high temperature environments [3]. Unfortunately, there are only a few vendors that have commercialized these processes specifically for high temperature. As has been reported earlier [4], [5], Quartzdyne, Inc., in partnership with its sister company Vectron International, has developed a hybrid process for its own circuits which has demonstrated high reliability in the down-hole environment. These circuits are used in precision pressure transducers sold by Quartzdyne.

Given the importance of this technology to Quartzdyne, it was considered judicious to establish a second source for hybrid circuits. Attempts to source the circuits from others in the industry fell short of our reliability expectations. We have worked with six other vendors over the last 12 years, but none (with the exception of Vectron) were able to supply circuits which could survive our rigorous qualification requirements. Given no other clear option, we found it necessary to develop a new facility at Quartzdyne which duplicates the Vectron process.

In establishing this facility, the following priorities were considered: duplicate the key elements of the Vectron process as closely as possible, improve repeatability of both component and wire bond attachment, and establish a lean, adaptable process capable of running multiple designs and variations simultaneously. Additionally, we recognized that the end-user of a down-hole tool does not distinguish between a transducer circuit failure and support circuitry failure – all elements of the system must function in order to obtain useable data. A transducer's ultimate reliability is dependent on the entire system's reliability. Consequently, it is in our interest to assist our customers in achieving the same reliability in their circuitry as we have in ours. The facility has been built with excess capacity in order to provide contract work for our customers.

Hybrid Process Overview

The standard process starts with an alumina substrate with Au alloy conductors. The metallization is chosen for compatibility with the various component attach methods and for reliability of wire bonds. Substrates are sourced externally. Both thick-film and co-fired ceramic processes have been qualified.

Components are attached with conductive and non-conductive polyimides as appropriate. Select devices are attached using eutectic solder or thermoplastic. An automated die bond system was acquired for this task (Figure 1). The system uses optical vision systems to identify components and pad locations in three dimensions. The bonder has a large array of tools online making it possible to perform component attachment using any of the above-mentioned methods without any changeover. We presently run four different designs simultaneously with no more changeover than loading the correct substrates and selecting the appropriate program. Component trays are easily switched in and out for different orders. Batches from 1 to 12 substrates can be run at a time. Two identical machines have been acquired to improve operator productivity and provide redundancy.

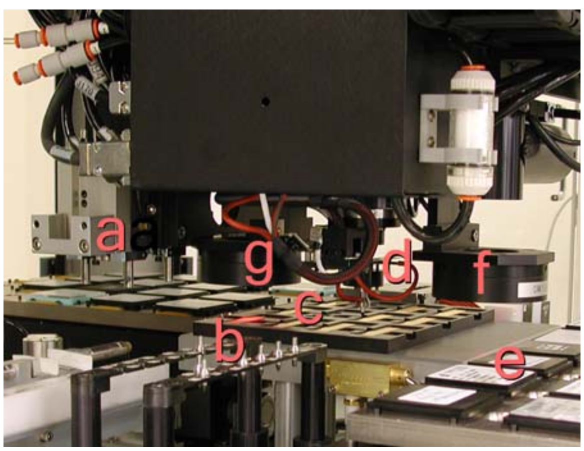

Figure 1. Automated Component Placement System: (a) polyimide dispense, (b) die collet holders, (c) substrates in placement area, (d) eutectic processing stage, (e) components in removable trays of waffle packs, (f) large area imaging camera, and (g) high resolution imaging camera.

Wire bonding incorporates both Au and Al wires based on the die metallization [6]. The metallization of the ceramic substrate is chosen to provide reliable connections for both wire types. A fully automated wire bond system was selected in order to provide repeatable and reliable wire bonds on the sometimes difficult to bond substrates (Figure 2). Prior to bonding, the system does a full mapping of the assembly, including z-height sensing for improved reliability. Additionally, the displacement vs. force profile during the actual bond process is monitored to assure consistent bonds. Custom bond tips have also been developed to improve the bond strength while providing access to high-density deep packages. The fully automated system is capable of working with small discrete devices as well as making quick work of high-pin count die (Figure 3).

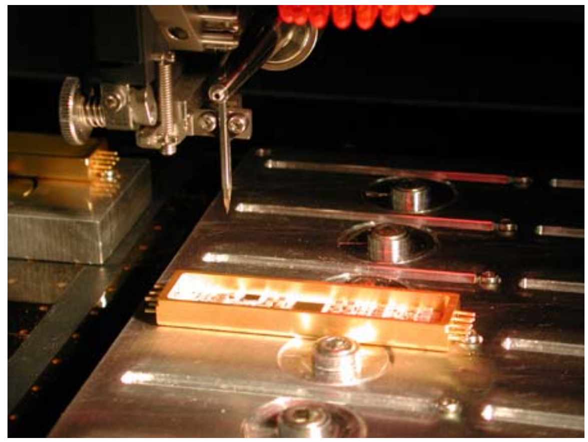

Figure 2. Automated Wire Bonder with Hybrid Circuit on heated parts stage: up to 12 parts can be loaded simultaneously.

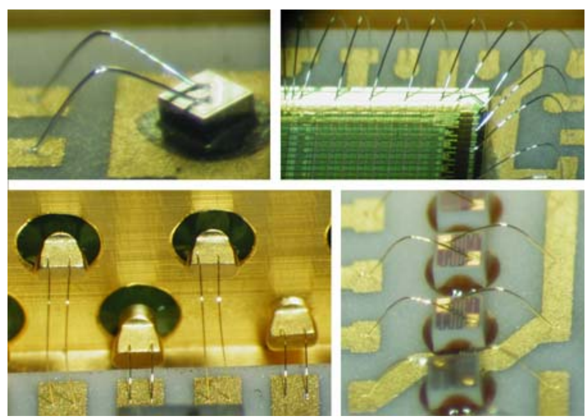

Figure 3. Wire bond samples: Al wires on a small transistor (top left) and a high-density FPGA (top right); Au bonds on staggered I/O pins (bottom left) and thin-film resistors (bottom right).

Production Unit Qualification Test Procedure

In order to verify the quality of the product, significant testing is required. Prior to sealing, all units are subject to exhaustive visual inspection and an electrical test. A sample from each lot is also taken for destructive wire pull and die-shear testing. Following welding, the units are subject to fine leak testing. All finished assemblies are then subjected to one week of aging at 225°C, 15 thermal cycles from 225°C to ambient, and 10 high impact drops. The thermal cycling and aging have been shown to weaken marginal interconnects. Subsequently, the high-impact drop test exposes the weakened joints. Additionally, the high g-levels during impact generate an effective 100% wire bond pull test. This suite of tests has proven to be extremely effective at weeding out infantile failures due to manufacturing defects.

Destructive Life-Testing of Sample Units

Building circuits for high-temperature down-hole use is a never-ending process of rigorous monitoring and continual improvement. Changes in components and materials that vendors think are benign often have negative impacts when components are stressed at high temperature. Left unchecked, once-stable processes have a tendency to creep out of control. Demands of the industry are ever increasing. In order to maintain reliability over the long-haul it is necessary to devote significant resources to monitoring and improving the quality of the process.

To accomplish this, Quartzdyne has established a suite of destructive tests to be performed on samples from each lot of products produced (Life/Cycle test). Each portion of the test suite is the result of identifying a particular failure (either in the field, or during processing), and then searching for a test that exposes that failure mode. Consequently, the tests have become more severe over time. They are purposely designed to induce failure, rather than mimic typical usage patterns.

Figure 4. Hybrid Circuits in Life/Cycle test being cycled from 225°C to ambient temperature.

The Life/Cycle test consist of three parts: time at temperature, thermal cycling, and mechanical shock. We have found that the combination of these tests is much more effective than the same tests performed separately. To simplify testing, units are not powered during the test. This is justified by the very low power consumption of the circuit under normal operation, and has been validated by powered tests performed on a smaller sample size.

Time at temperature and thermal cycling are accomplished using forced-air convection ovens running continuously at either 225°C or 250°C (Figure 4). [Surface mount circuits (SMT) are tested in a similar fashion, albeit at reduced temperatures of 150°C and 180°C.] Samples are left in the ovens over night and on weekends. Each working day, the samples are removed from the ovens and allowed to cool to room temperature for approximately 30 minutes, after which they are returned to the ovens for a minimum of one hour. The process is repeated such that each sample receives 15 thermal cycles and 160 hours of time at temperature each week. Every two weeks the units are tested electrically.

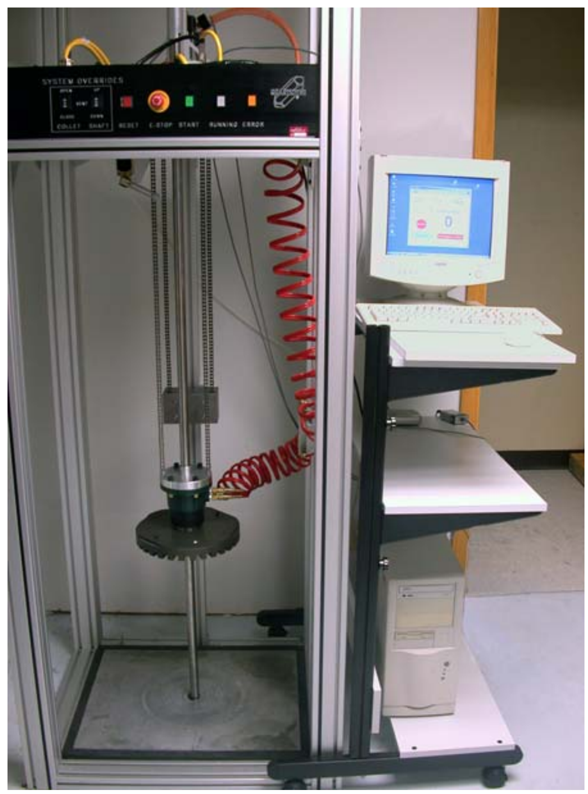

Figure 5. High-impact Drop Fixture. Under computer control, a pneumatic collet lifts the parts carrier to a pre-determined height and then releases it. A sleeve bearing keeps the carrier level during the fall.

A portion of the test sample is also subjected to high-impact shock testing. The test is a free-fall with a metal-to-metal impact, repeated 25 times. The impact is not instrumented, as we have not found an accelerometer capable of surviving this test. We estimate the impact to be approximately 1 million g's in 1 microsecond based on extrapolation of data measured at lower impacts. This sequence is repeated biweekly until 100 drops have accumulated.

Prior to 1998, a sample of each lot was tested until a milestone lifetime was achieved, as a lot qualification. Beginning in 1998, the test policy was changed such that all circuits in the sample test are tested to destruction. Since then nearly 8 million device test-hours have been logged (Table 1). The volume of test data generated is statistically significant. It provides the ability to predict field life under typical conditions and it provides valuable feedback for process improvements.

Table 1. Life/Cycle test matrix (Since 1998)

Test	Qty Tested	Total Hours	MTTF
SMT (150°C)	250	2,175,401	4,766
SMT (180°C)	484	843,662	618
SMT (200°C)	2	1,392	696
Hybrid (225°C)	401	4,635,184	18,492
Hybrid (250°C)	74	148,961	1,863
QD Hybrid (250°C)	39	71,811	3,531
Total	**1250**	**7,876,411**	

Test-driven Improvements

Several process improvements have been made since the hybrid was first developed in January 2000. Figure 6 shows the lifetime and failure mode of each hybrid tested at 225°C as a function of when it was built. The graph is useful in identifying key failure modes, and how these have been affected by process changes. Each unit is represented by an "**x**" if it has failed, or by an open triangle "**Δ**" if it continues to survive. Surviving units follow the elapsed-time curve upwards. When a unit fails, it becomes fixed on the graph. The failure modes for each unit are indicated by various colored shapes. Groupings of early failure modes are readily apparent. As each new failure mode is recognized, efforts are made to address it. The Large-Q and Small-Q problems were addressed with material changes. The Capacitor problem was addressed with process changes. The Wire problem is being addressed by nondestructive bond pull testing, and with the automated wire-bond process discussed earlier.

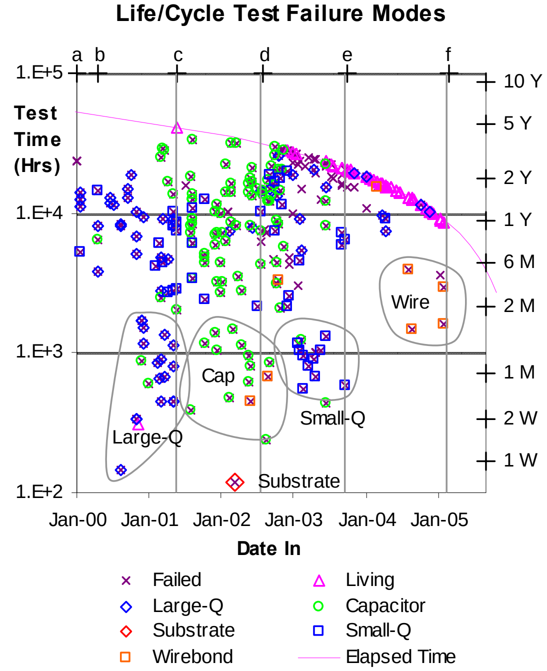

Figure 6. Test times for production hybrid units in Life/Cycle test. Failed units are denoted with an "x"; open triangles "Δ" indicate units still surviving. Dominant failure modes are indicated for early failures. Key process changes are are identified by letters across the top of the graph: (a) initial prototypes, (b) first production units, (c) attach material for large transistors, (d) process change for cap and substrate attach, (e) attach material for small transistors and 100% drop screen, and (f) 225°C test discontinued.

As can be seen, the process changes noted have been effective at improving the life-time of units in the test. In fact, they have been so effective that the test no longer has value as an early indicator of problems; a typical unit now survives more than a year before we find its weakness. In order to provide feedback on process quality in a shorter time frame, the test temperature has been increased to 250°C for all units made since 2005.

Comparison of Hybrid to Surface Mount

While Hybrid reliability has been steadily improving, Life/Cycle test results have shown a significant decline in the reliability of Surface Mount boards. Figure 7 shows the survival functions [7], [8] for both hybrids and surface mount boards built prior to July 2001 and after July 2001. Each dot on the graph represents a unit in test. The y-axis value is the percentage of units that have survived at least that long. The smooth lines are best-fit Weibull distributions [9]; the solid lines are for units built after July 2001 and the dashed lines are for units built prior to that date. The dots for pre-2001 units have been removed for clarity. The improvement in hybrid life is in sharp contrast with the reduction in surface mount life. The latter correlates to changes in formulations of the plastic encapsulants used in integrated-circuit packages over that time period [2].

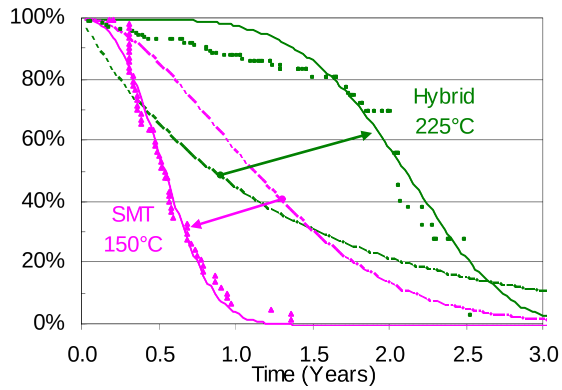

Figure 7. Survival Rate plotted at each failure time for circuits built after 7/1/2001 (Dots). Solid lines are best-fit Weibull Survival Function for the same. Dashed lines are best-fit survival functions for circuits built prior to 7/1/2001.

The survival functions of Figure 7 can be plotted versus test temperature as shown in Figure 8. The 50% survival points are plotted, with error bars indicating the 10% and 90% points. We have also included the data for surface mount units tested at 180°C and hybrid units tested at 250°C. Hybrid units made at Quartzdyne and Vectron are plotted separately. While the data for units produced by Quartzdyne is early (October 2005 – February 2006), it does compare favorably with units produced at Vectron for which we have significantly more data. The correlation between the Quartzdyne and Vectron data also suggests that new designs produced on this mature process can be expected to function similarly, and can thereby leverage the historic test results.

Using the graph of Figure 8, it is possible to predict field life at various temperatures. When doing so, it is important to recognize that the stresses experienced in the field may not be the same as those simulated in the test. Actual field conditions must be considered when making life projections.

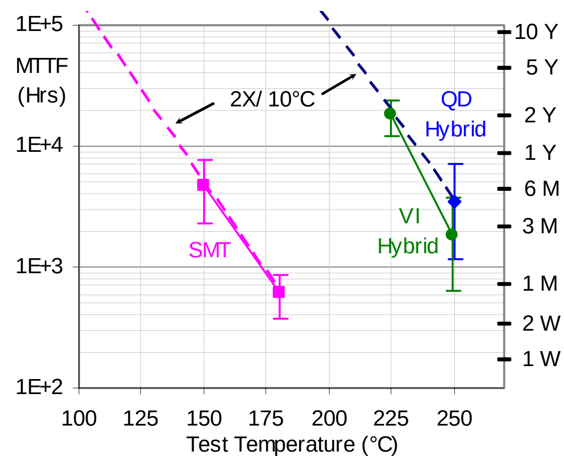

Figure 8. Time to 50% failure for various circuit technologies in Life/Cycle test since July 2001 (error bars at 10% and 90%). Nominal de-rating of 2X/10°C is shown for reference.

Field Returns

Figure 9 shows the field return rates for hybrid circuits produced over the last five years [10]. Although we do not typically have data on what conditions a particular unit has seen in the field, we do analyze every field failure. The high return rates for 2001 and 2002, while possibly typical for a new process, are clearly unacceptable. The majority of these failures were for substrate detachment. Once this failure mode was identified, process changes and screens were implemented to address it. No parts manufactured with the new process have failed in the field for substrate detachment. (Note that the actual number of units shipped in 2001 was relatively small, and most of the units shipped were used in customer qualification tests.)

Other field-return failure modes correlate to the failure modes seen in testing. With steady incremental improvements, the process has matured to the point that less than 2% of circuits made since 2002 are expected to fail after five years in the field. This failure rate should continue to decline as the process continues to improve.

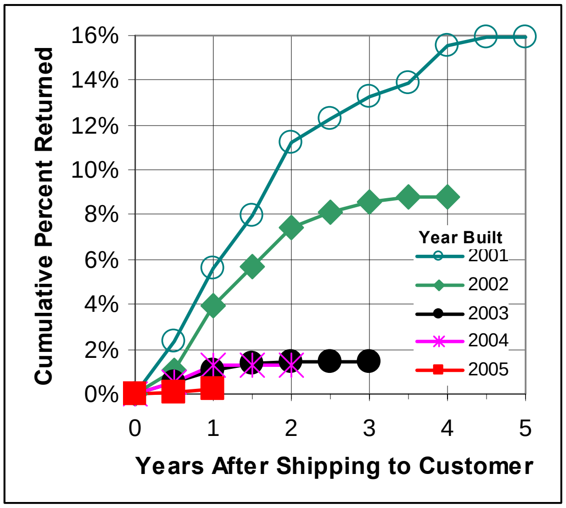

Figure 9. Cumulative customer return rate for Hybrid circuits. Each line represents the number units shipped in a given year that were returned for Hybrid circuit failure. The x-axis represents the number of years the unit was in the field before it was returned. The last two points of each series may still rise as the periods are not yet closed.

Conclusion

Providing high-temperature electronic circuits to the down-hole oil and gas market requires extreme vigilance in order to provide the highest quality products possible. When pushing the limits of components and materials it is important to continually monitor the process, identify weak links, and work towards improving the product. The process available at Quartzdyne is capable of supplying hybrid circuits that meet the rigorous demands of the down-hole industry.

Acknowledgements

The author would like to thank Jacob Li of Vectron International for his cooperation in developing the Hybrid processes. Also, sincere thanks to Mark Hahn, Chris Hahn, Lisa Chase, and Brandi Maag for their tireless efforts in fine-tuning the process at Quartzdyne.

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