INCREASING HIGH-TEMPERATURE RELIABILITY OF PLASTIC ICs USING DIE EXTRACTION, GOLD BALL REMOVAL, AND ENEPIG DIE PAD PLATING (*DEER*)

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ABSTRACT

Integrated circuits can frequently operate above their maximum rated temperature of 125°C, but are not packaged appropriately to reliably endure higher temperature exposure. Specifically, the plastic packaging can rapidly degrade at temperatures greater than 125°C. Furthermore, even if the plastic packaging is able to maintain its integrity at higher temperatures, the original gold or copper bonds on the aluminum die pads are prone to Kirkendall or Horsting voiding, particularly at temperatures greater than 150°C. In some cases, commercial demand for higher temperature performance and packaging can justify support of a ceramic line from the original component manufacturer (OCM). In most cases, the demand is insufficient.

Global Circuit Innovations (GCI) has developed a high-yielding extraction process, which can take a die out of a plastic package, remove the original bond wires and/or ball bonds, plate the aluminum die pads with electroless nickel, electroless palladium, and immersion gold (ENEPIG), and finally reassemble and re-bond the die within a hermetic, ceramic package. Device Extraction and ENEPIG pad plating and Repackaging (*DEER*) provides a die pad surface such that either gold or aluminum wire can be used for applications up to 250°C without connectivity degradation. GCI routinely exposes devices to 250°C bakes for thousands of hours with 100% post bake yields to continuously ensure that any device processed with the *DEER* technology will reliably perform in high-temperature environments.

Although the oil and gas industry has already expressed significant interest in the *DEER* process, with excellent life test and application results regarding dramatically increased component lifetimes at elevated temperatures, this technology can also be leveraged for any application exposing ICs to harsh environments. Not only is the high-temperature reliability dramatically increased, but also the new hermetic, ceramic package protects the IC from a variety of elements and environments (i.e., corrosives and moisture).

INTRODUCTION

Global Circuit Innovation's *DER* processes (see Figure 1 below), specifically including electroless nickel, electroless palladium, and immersion gold (ENEPIG) die pad re-conditioning (combined acronym of *DEER*), was developed to provide a reliable extraction and re-packaging solution that resolves undesired compound wire bonding (new bond on original bond) during reassembly, particularly for military applications. This process also provides a new die pad surface medium for either aluminum or gold wire bonding that ultimately prevents subsequent gold/aluminum interface degradation (Kirkendall or Horsting Voiding) at temperature exposure greater than 150°C.

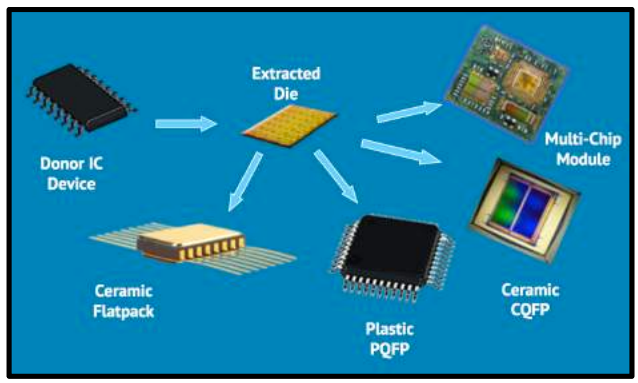

Figure 1. GCI's *DER* Process Illustration

Following gold ball removal, the exposed aluminum pads of the extracted die are then reconditioned using a sequence of plating steps to form the ENEPIG finish (see Figure 2 on following page). This electroless plating process is well proven in the electronics industry and is in wide-spread use for applications such as solder flip chip interconnections as well as a surface finish for printed circuit boards (PCBs) with excellent wire bond capability.

The ENEPIG process for re-conditioning aluminum die pads involves a sequence of wet process steps that begins with zincating the aluminum pad. This zincating step allows nickel to grow on the zincated surface in the subsequent nickel bath. Since the nickel-plating process is electroless, the bath chemistry and bath temperature, as well as the length of time the device is in the bath, determine the thickness of the nickel. Once the desired nickel thickness is obtained, the device is immersed in another electroless bath where palladium grows selectively on the nickel surface. The thickness of the palladium is also determined by bath temperature and chemistry as well as length of time the device is immersed in solution. As a final step, the IC is exposed to an immersion gold bath where a few monolayers of gold self-deposit on the palladium surface in a self-limiting reaction. None of these steps require masking. The thicknesses of these plated layers can be determined by a number of analytical techniques such as cross section analysis, and X-ray Fluorescence Spectroscopy (XFS).

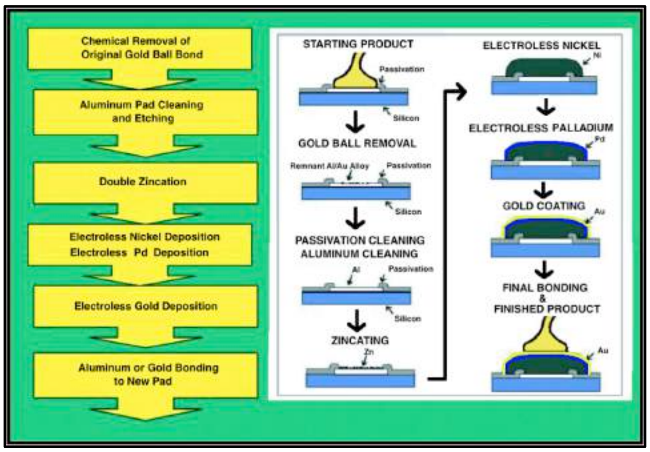

Figure 2. GCI's *DEER* Specific *DER* Process Flow Including Gold Ball Removal and ENEPIG Pad Re-conditioning. Target: 4 µm Ni, 0.25 µm Pd, & 0.04 µm Au

The appearance of the *DEER* process can be seen in optical and SEM photos within Figures 3 and 4, respectively.

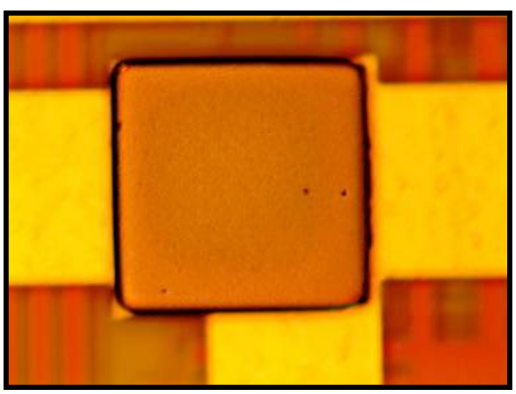

Figure 3. Optical Photo of ENEPIG Plated Die Pad

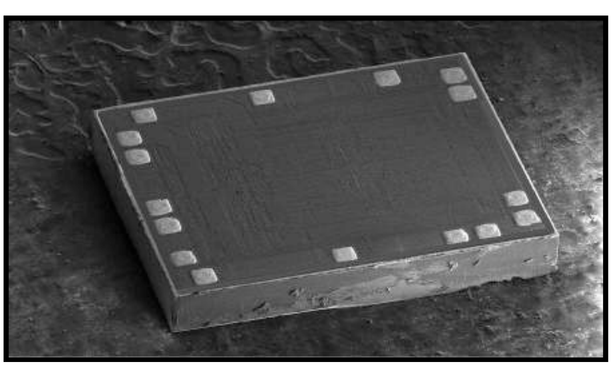

Figure 4. SEM Photo of Die with ENEPIG Plated Pads

Additionally, the GCI ENEPIG process version of *DER*, or *DEER*, is scheduled to be qualified within the next year to meet or exceed the challenging requirements of MIL-STD 883 test methods with upcoming Department of Defense (DoD) sponsored qualification builds and electrical reliability testing (including dynamic burn-in), comparing the *DEER* IC product relative to their actual plastic controls (donor devices). The basic *DER* process was MIL-STD 883 qualified on at least three IC devices in the past 24 months.

Relative to general harsh environment applications, the new *DEER* process has already been proven to be capable of meeting the stringent requirements involved with high-temperature integrated circuit (IC) reliability for the oil and gas drilling industry, including 1000g+ shock and vibrational testing, high-temperature reliability at 250°C beyond 6,000 hours, and tens of thousands of hours of field functionality. Because of these extraction and re-packaging technologies, there now also exists many potential commercial options to generate military IC product solutions using GCI's *DEER* processes for otherwise obsolete components. Bare die (see Figure 5 below) can also now be made available for either the exact replacement or similar die function though GCI's extensive, time-proven processes, ultimately producing a variety of environmentally hardened replacement solutions.

Figure 5. Bare Die Inventory Using *DER* or *DEER*

ENEPIG PLATING

ENEPIG plating was originally developed as a surface finish for printed circuit boards (PCBs) that needed both solder joints as well as wire bond interconnections[1]. ENEPIG not only forms a solderable surface that avoids gold embrittlement of solders, but also has superior wire bondability and corrosion resistance. Furthermore, since less gold is used in an ENEPIG finish than traditional gold-based finishes, processing costs are reduced. ENEPIG now sees widespread acceptance in the PCB industry.

The ENEPIG process is well suited for both aluminum and copper surfaces since it is an auto-catalytic reaction[2]. It can be deposited on those surfaces without an external electrical bias connection for plating as would be required in conventional electroplating. Process parameters such as time, temperature, and chemistry, as well as the quality of the original surface, impact the rate and quality of electroless ENEPIG depositions, and the process is robust and reasonably easy to control. Literature has shown that improvements in reliability are obtained with a wide range of ENEPIG layer thicknesses on virgin aluminum pads. Researchers have typically targeted nickel thickness range from 4 to 6 microns, followed by 0.2 to 0.4 microns of palladium with a final layer of about 0.05 microns of gold[3]. The palladium thickness is the more critical parameter since this layer provides a corrosion barrier between the nickel and gold, and since palladium is about half of the hardness of nickel, it significantly broadens the wire bond process window, (see Figure 6 below) thereby decreasing pad cratering or pad delamination[4]. GCI's ENEPIG process has also targeted those thickness values.

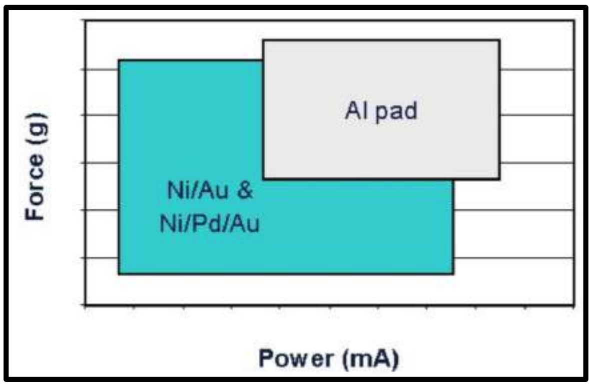

Figure 6. Comparison of Wire Bond Process Parameters for Aluminum and ENEPIG Pads.

DISCUSSION OF *DER* TECHNOLOGY AND *DEER* BENEFITS

Conventional die extraction methods typically leave some portion, or all, of the original bond present - see Figures 7 and 8 for optical and Scanning Electron Microscope (SEM) photos of remnant gold balls, respectively. Subsequent bonding of extracted die would necessarily create a compound bond. Compound bonding of these remnant balls produces bonds similar in appearance to the SEM image seen in Figure 9 (containing compound and single bonds).

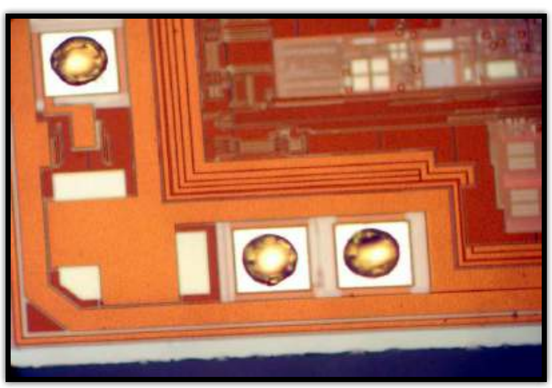
Figure 7. Extracted Die with Remnant Gold Balls (Optical Photo)

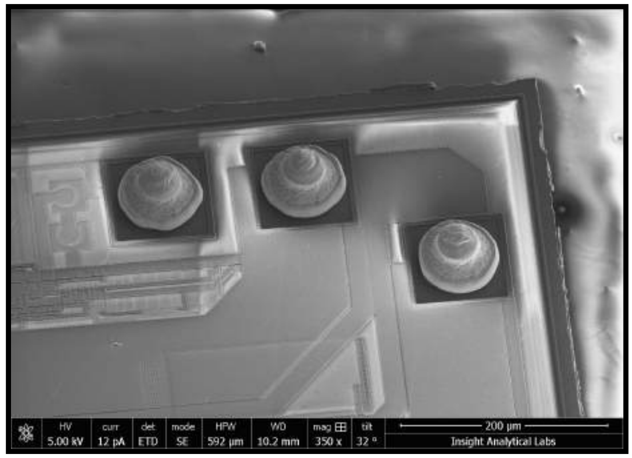

Figure 8. SEM Image of Extracted Die with Remnant Gold Ball.

Global Circuit Innovations addressed the compound bond issue and Kirkendall voiding of the original gold wire on aluminum pad at high-temperatures (i.e., > 150°C) by first developing a process to eliminate the remnant gold balls present following extraction.

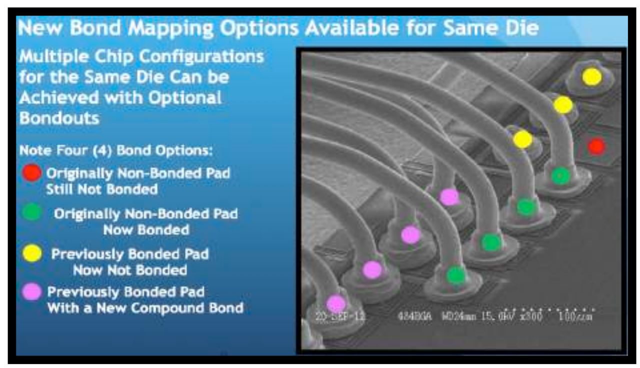

Figure 9. SEM Image of Compound and Single Bonds

In general, compound bonds are viewed as less reliable due to multiple bonding surfaces, particularly in high vibration or high G-force environments. Additionally, temperature exposures >150°C increase the risk of intermetallic diffusion and voiding for gold ball on aluminum pad bonding (see Figure 10).

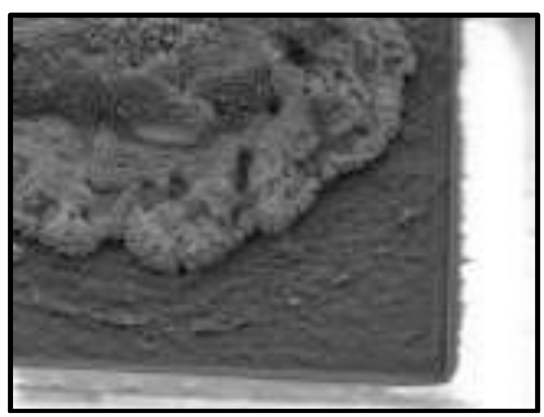
Figure 10. General Appearance of Kirkendall or Horsting Voiding. Gold Ball Bond Lifted due to Au-Al Degradation.

This particular high-temperature phenomenon presents a renowned reliability risk due to the degradation of the electrical and mechanical interface between the gold bond and aluminum pad by Kirkendall or Horsting voiding and degradation due to intermetallic formation at the Au-A1 interface. Specifically, at the gold ball to aluminum bond pad interface, the following intermetallic compounds can be formed: Au_5Al_2, Au_4Al, Au_2Al, $AuAl_2$ (all of which are brittle and non-conductive).

These intermetallics are mechanically weak, and the change in phase structure for these metals can create voids. At elevated temperatures, these metallic phase changes can happen quite rapidly. This failure mechanism can result in the loss of electrical connection between the IC pad and the wire, thus causing the IC to fail (see Figure 11), is accelerated by elevated temperature, and thus it is often the limiting factor when using ICs with gold bond wires packaged in plastic packaging in long life, high temperature applications.

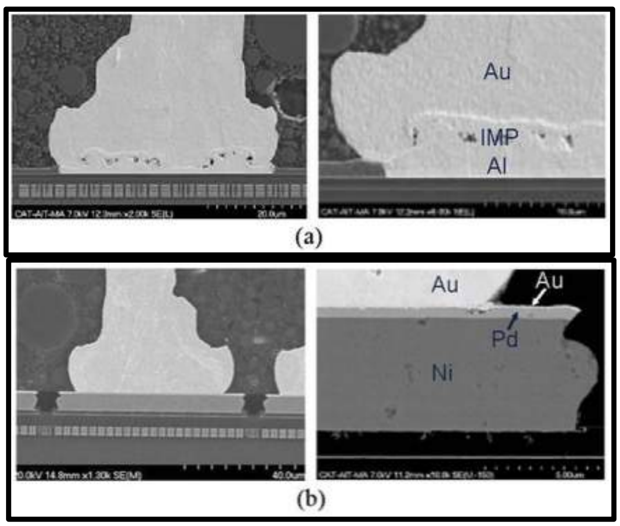

Figure 11. (a) Gold Ball Bond on an Aluminum Pad showing undesired Intermetallics. (b) Gold Ball Bond on an ENEPIG Pad showing no Intermetallics.[3]

Typically, gold balls bonded on aluminum pads have shear failures near the metallic interface, whereas gold balls bonded on ENEPIG pads show metallic failure in the ball itself. This shows greatly improved mechanical adherence at the ball-pad interface. These two conditions are illustrated in Figure 12.

Ultimately, using the *DEER* technology, the original pad is re-conditioned to provide a new bonding surface. With subsequent gold or aluminum wire bonds on the ENEPIG pads, no intermetallic diffusion is experienced up to 6,000+ hours at 250°C. This has been proven empirically with 250°C unbiased baking as seen in Figure 13 below.

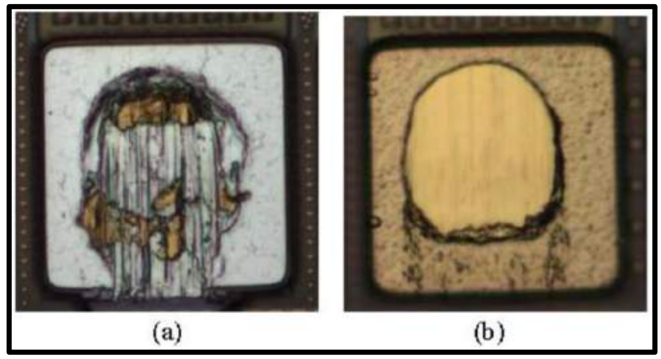

Figure 12. (a) Aluminum Bond Pad after Gold Ball Bonding and Shear Test, (b) ENEPIG Plated Bond Pad after Gold Ball Bonding and Shear Test.[1]

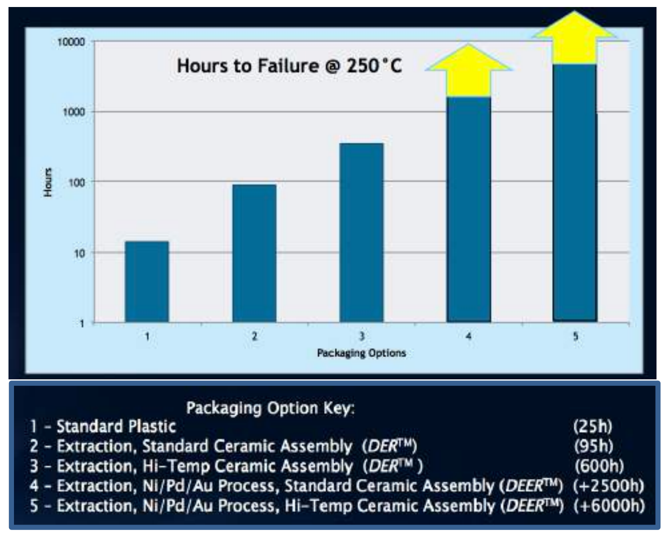

Figure 13. Ni/Pd/Au Pad *DEER* Re-Plating Performance at 250°C, with Packaging Option Key Explained

The various packaging options within Figure 13 can be explained in more detail as follows:

1.) Hours to connectivity failure at 250°C exposure in the standard commercial plastic encapsulation
2.) Hours to connectivity failure at 250°C for a standard plastic encapsulated device which has been extracted and with the *DER* process re-assembled and with a conventional ceramic package process
3.) Hours to connectivity failure at 250°C for a standard plastic encapsulated device which has been extracted with the *DER* process and assembled with a vacuum-baked, lid seal process incorporating a very dry inert cavity gas with moisture getter in a ceramic package
4.) Hours to connectivity failure (non-existent) at 250°C for a standard plastic encapsulated device which has been extracted with the *DEER* process and assembled with a conventional ceramic packaging process
5.) Hours to connectivity failure (non-existent) at 250°C for a standard plastic encapsulated device which has been extracted with the *DEER* process and assembled with a vacuum-baked, lid seal process incorporating a

very dry inert cavity gas with moisture getter in a ceramic package.

To date, there has not been a reliability performance variation seen between packaging flows 4 and 5 above using *DEER* extracted devices, thereby indicating that conventional ceramic packaging of *DEER* product is just as reliable as using much more complex and expensive packaging techniques requiring bake-outs and desiccants for moisture control. Thus, *DEER* bare die can be made available for conventional processing with multi-chip module (MCM) assemblies as well as monolithic packaging.

SEM photos of subsequent gold wire bonding on the ENEPIG pads can be seen below in Figures 14 and 15, respectively. Note that Figure 14 reveals the presence of a slight amount of remnant gold/aluminum alloy following gold ball removal, which has been subsequently plated, yet has not been seen to adversely affect quality or reliability. Figure 15 does not have this appearance, because it originally had copper wire which does not leave an alloy formation following extraction.

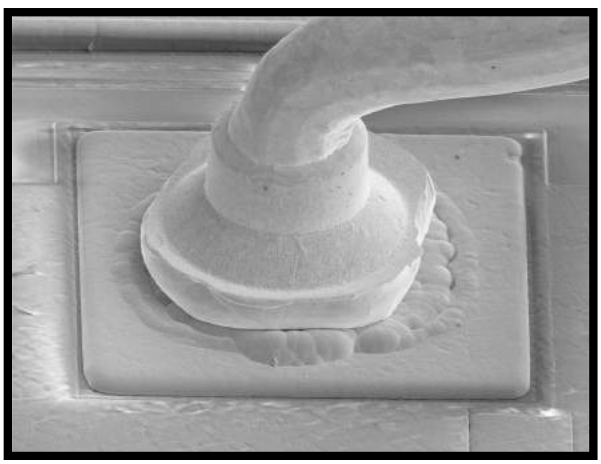

Figure 14. Gold Ball Bond on ENEPIG plated Die Pad originally bonded with a Gold Ball

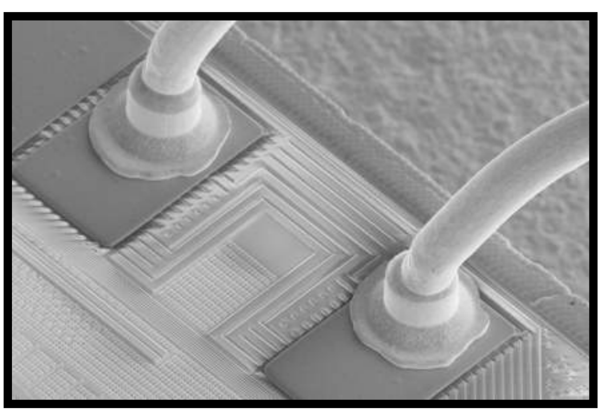

Figure 15. Gold Ball Bond on ENEPIG plated Die Pad originally bonded with Copper Wire

Lastly, Figure 16 graphically illustrates the strong contrast in performance for bond pull strengths relative to aging at 250°C for gold wire bonds on ENEPIG and aluminum pads, with the gold/aluminum interface degradation being responsible for the very sharp decrease in bond strength. This phenomenon does not occur for the gold/ENEPIG bonds. Similar to what was qualified with respect to *DER* processing, the *DEER* technology and packaging is also expected to greatly exceed high-end commercial reliability

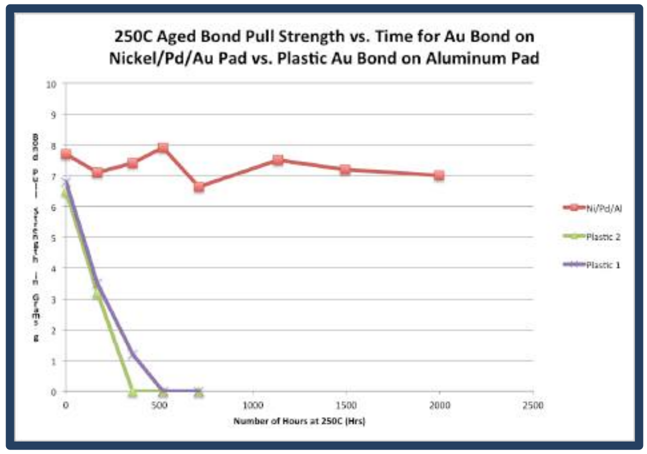

Figure 16. Bond Pull Strength vs. Time at 250°C for ENEPIG Pad Plating within Ceramic Packages vs. Conventional Aluminum Pads in Plastic Packages

standards within Department of Defense (DoD) MIL-STD 883 testing, including Groups A, B, C, and D, 1000 hour +125°C dynamic life test, and 1000+ hour 250°C unbiased baking.

CONCLUSION

Commercial integrated circuits have significant reliability limitations at elevated temperatures due in large part to the lack of hermetic packaging and the formation of undesired intermetallics at the interface between the aluminum bond pads on the IC and gold wire bond that connects the pad to the IC package. It is well known that die extraction/ reassembly (*DER*) of commercial integrated circuits into ceramic packages increases the reliability of those devices. By further reconditioning the aluminum pads on commercial die with a plated ENEPIG (Electroless Nickel, Electroless Palladium, Immersion Gold) layer, all known failure modes associated with the formation of Al-Au pad intermetallics can be entirely eliminated.

GCI has successfully demonstrated the manufacturability and benefit of plated ENEPIG films to enhance the reliability of commercial ICs that have been extracted from their original packages and reassembled into ceramic packages (*DEER*), while eliminating compound bonding with tens of thousands of devices in the field for high-temperature, high-vibration, high-reliability, and rugged applications. A thorough reliability study involving MIL-STD 883 qualification for the *DEER* process is currently underway, and is expected to pass all qualification requirements, as did the basic *DER* technology previously. Lastly, the oil and gas industry is currently using tens of thousands of ICs processed with the *DEER* process in the field, providing dramatically increased component lifetimes at elevated temperatures. This technology can now be leveraged for applications exposing ICs to any number of harsh environments by creating hermetic solutions from IC's in plastic packages to produce devices which will work in a variety of extremely harsh environments (corrosives and moisture).

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TRADEMARKS

Die Extraction and Reassembly – *DER*™, Global Circuit Innovations (2017)

Die Extraction and Reassembly with Gold Ball Removal and ENEPIG Die Pad Plating – *DEER*™, Global Circuit Innovations (2018)