300 Degree Celsius Electronic Component Packaging

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Abstract

Characterizing geothermal wells and their surrounding geothermal formations requires the use of electronic subsurface logging tools that monitor conditions (e.g. temperature, pressure, flow, fluid chemistry); unfortunately, few electronics can gather and transmit accurate data at temperatures exceeding 200 ˚C. The most common workaround is to place a low temperature electronic device inside a vacuum flask, which slows the migration of heat transfer from the surrounding rock formation, but the drawback to this approach is that the tool is limited to a few hours of operation before it needs to be removed from the geothermal well. Enhanced geothermal systems require long-term characterization, with tools and downhole monitoring systems that can be emplaced for months at a time. At Sandia National Laboratories, the Geothermal Department is focused on developing subsurface tools that can operate for a month or more at temperatures reaching 300 ˚C. At present, we are developing a range of electronic packaging techniques that integrate off-the-shelf high-temperature surface mount integrated circuits onto ceramic printed circuit boards, with gold-tin solder and wire bonding, along with a conformal coating to improve reliability. These four-packaging techniques have been evaluated at 300 ˚C towards the goal of demonstrating a 300 ˚C datalink that uses a RelChip RC10001 microcontroller for geothermal well evaluation.

Key words

Geothermal, High Temperature, Packaging, Ceramic, Gold-Tin, Wire bonding

I. Introduction

Characterizing geothermal wells can be challenging because state-of-the-art subsurface sensors generate low analog signals that cannot travel long distances; the signal can easily fall below the noise floor as it propagates through the 5,000–10,000+ feet of cable leading back to the surface. The most common solution is to store the sensor's digitized data into local memory within the tool and retrieve the data when the tool is returned to the surface. However, to obtain real-time signal data from the sensor, the low analog signal must be converted into a digitized signal by an embedded electronic system (EES) comprised of a microcontroller and other components to conduct local signal processing placed near the sensor. In that case both the sensor and the EES must be qualified for high-temperature (HT) operation because geothermal wells often operate at temperatures of 200 °C–300 °C+. At present, there are few commercially available components that can reliably operate above 200 °C.

Sandia National Laboratories main objective is to test and evaluate a packaged EES that can operate at temperatures ≤ 300 °C. Sandia recently completed a study with the RelChip's RC10001 microcontroller in a surface mount device (SMD) configuration, the only modern microcontroller on the market that can operate at 300 °C. Several challenges were observed using standard packaging techniques and using the devices at 300 °C. Here, we describe our evaluation of four HT packaging techniques: ceramic printed circuit boards (PCB), gold-tin soldering, wire bonding, and/or conformal coatings to resolve the challenges observed with the SMD packaging. If the techniques proposed are successful, this would enable the required electronics for long-term ≤ 300°C operation for geothermal subsurface instrumentation for characterization of deeper/hotter wells.

II. 300°C Challenges

Viable HT ICs are generally built as either thru-hole devices, surface-mount devices, or dies (diced wafers that contain the circuit before it is emplaced in a thru hole or SMD package). SMD are desirable because the device requires a smaller footprint than thru-hole devices, reducing the size/cost of the

EES. Consequently, HT SMD ICs are more commonly available on the market. However, we identified three challenges for SMD ICs operating at temperatures reaching 300 °C.

Challenge 1: Common PCBs including low-cost, readily available Roger materials (i.e. RO3003, RO4003) and polyimides (i.e. Arlon85N), which maintain performance at temperatures reaching 260 °C, breakdown when exposed to 300 °C temperatures. The material begins to decompose, undergoing both dielectric-to-metal delamination and dielectric-to-dielectric delamination (Figure 1), which strains the electrical connection between the PCB and the SMD IC.

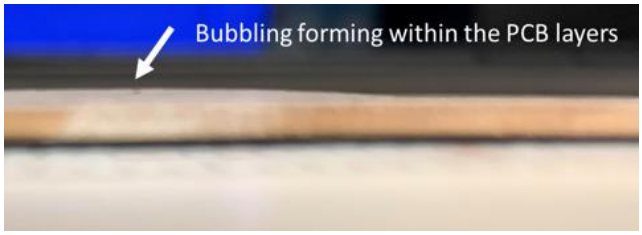

Figure 1: Rogers4003 PCB cross-section, with a bubble forming between the multilayer board after baked at 300˚C.

Challenge 2: The most common HT solder is 93.5Pb/5Sn/1.5Ag, which has a melting point of 301 ˚C. At 300˚C, the solder is reaching the liquidous point, at which it begins to react with the gold plating on the pins of the off-the-shelf SMD IC. As the gold fuses into the solder, the solder degrades and weakens the electrical/mechanical connection between the SMD and PCB. Gold plating is necessary on HT SMDs because they do not oxide under the HT conditions.

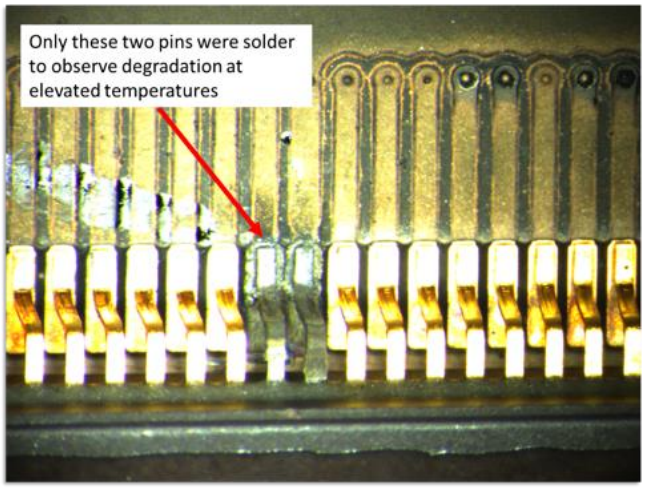

Figure 2: Two pins of the IC had been soldered with observation of the gold wicked into the HT solder.

Challenge 3: All materials have a temperature-dependent coefficient of thermal expansion (CTE). If the IC materials and PCB materials have a different CTE, the PCB can expand more rapidly than the IC, causing strain between the IC and PCB.

Each of these challenges can drive the SMD to debond from the PCB and, thus, loss of EES functionality. To correct for these challenges, Sandia is exploring alternative materials and techniques.

III. Packaging Techniques

To improve the reliability of off-the-shelf ICs packaged onto PCBs for 300 ˚C operation, our team has explored four factors: the PCB material, the electrical connection between IC and PCB, and the conformal coating over the IC and electrical connections that protects them from the harsh HT environment. Sandia is exploring ceramic as the PCB, gold-tin (Au/Sn) solder, wire bonding, and HT epoxy for the conformal coating.

A. Ceramic Printed Circuit Boards

Ceramic can operate well above 300 ˚C and is commonly used for applications where ICs produce excessive heat. Since the material is commonly used for PCBs, the material is readily available for the industrial manufacturing. For this study, Sandia has been evaluating ceramic (Al_2O_3) (Fig. 3).

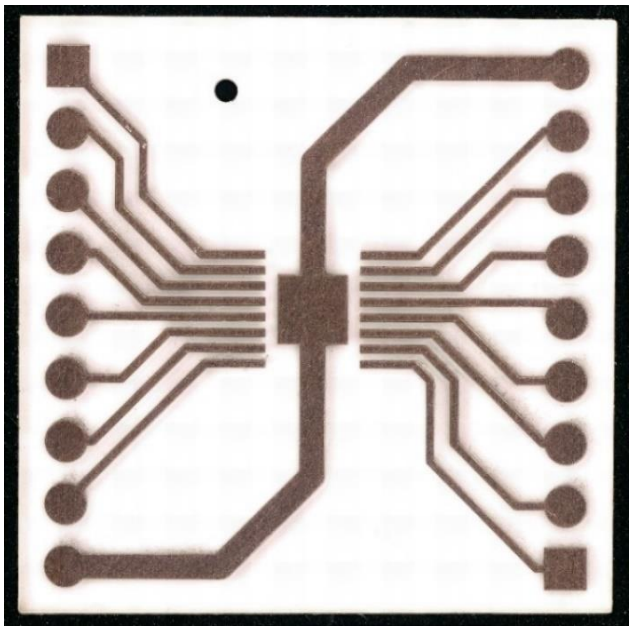

Figure 3: PCB circuit etched onto Al_2O_3 with a thickness of 0.020". The copper is attached via a titanium layer.

Sample PCBs were processed in three steps: (1) a metal plating is deposited on the surface of the ceramic, a seed layers (bonding agent) of titanium (Ti) and (2) copper (Cu) are applied to the Ti surface, and (3) a pattern is laser etched through the Ti/Cu to create a PCB with a TDFP16 SMD footprint to match Cissoid's CHT-RIGEL voltage regulator (which has a thermal protection of 250–300 ˚C). After one month of exposure to 300 ˚C, no observed bond degradation

was observed with the Al_2O_3 PCBs.

B. *Gold-Tin Solder*

Having evaluated a non-degrading PCB, the next step of the effort is to evaluate the electrical bonding of the IC with gold-tin (Au/Sn) solder. The first step is to apply a metal plating to the copper surface of the PCB, which limits corrosion and improves bonding with the gold-tin solder. We chose the electroless-nickel electroless-palladium immersion-gold (ENEPIG) plating pattern commonly used for wire bonding die ICs: Ti/Cu/Nickel (Ni)/Palladium (Pd)/Gold (Au), with a targeted thicknesses of 150/750/250/250/250 nm, respectively. Once the plating is complete, we applied a Mitsubishi Materials USA gold-tin (Au78/Sn22) solder with specific particle size (5-16µm), flux type (AS1), viscosity (90Pa-s), and solidus/liquidous states (278 °C and 301 °C).

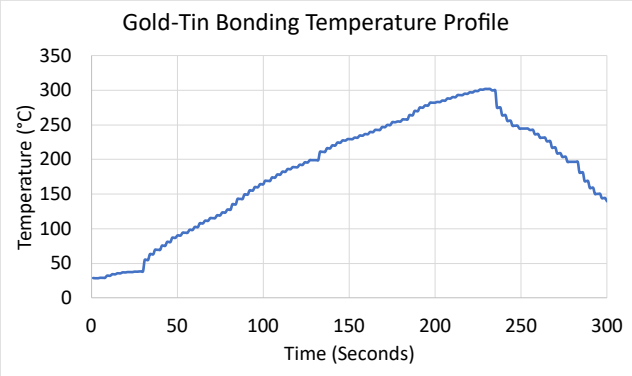

Figure 4: Four-stage Sikama oven temperature profile for the Au78/Sn22 solder.

The SMD was bonded to the PCB with the gold-tin solder in a four-stage Sikama oven with a running a temperature profile (Figure 4). A populated PCB (Figure 5) was then evaluated at a constant temperature of 300 ˚C for three weeks. While no delamination of the SMD IC from the PCB was observed, the high temperatures changed the color of the metal traces from the gold color to a black color. It is believed that the Ti/Cu/Ni/Pd/Au metals fused together.

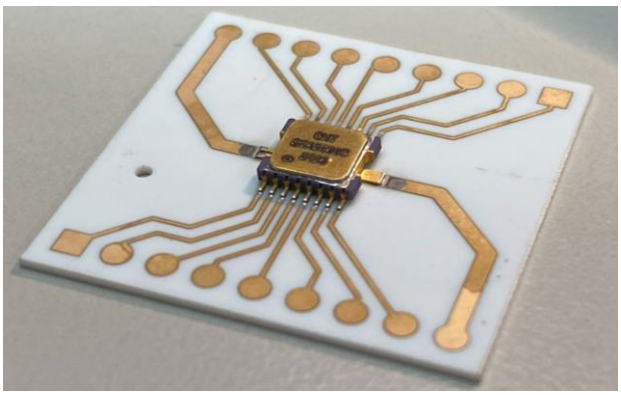

Figure 5: Al_2O_3 with ENEPIG plated circuit with a gold/tin bonded CHT-RIGEL IC.

Repeating the test, wires were attached to a newly packaged PCB with the CHT-RIGEL SMD and connected to a power supply which was placed outside the oven. The electrical testing revealed that the IC is functional below 270 °C but has a thermal protection functionality between 280–290 °C which would disable the voltage output of the voltage regulator. The experiment continued with the temperature set to 300 °C for a 1-week duration. After cooling the device back down to 270 °C, the voltage regulator would go out of thermal protection mode and produce a 5 V signal indicating the device and Au/Sn packaging survived. Going forward, we plan to test the packaged PCB under vibration at 300 ˚C, which will reveal whether the gold-tin is entering a liquidous state and/or if there is degradation of the solder joint due to the fusion of the deposited metal layer.

C. *Chip-on-Board Wire Bonding*

Alternatively, to gold-tin bonding, an unpackaged (die format) IC can be directly attached to the ceramic PCB via wire bonding. The advantage of this approach is that the wire bonds can act as a strain relief for the electrical connection. The disadvantages are that only some of the industrially produced HT ICs are sold in a die format and the die is significantly more fragile than an SMD IC, which makes it more vulnerable to damage during packaging.

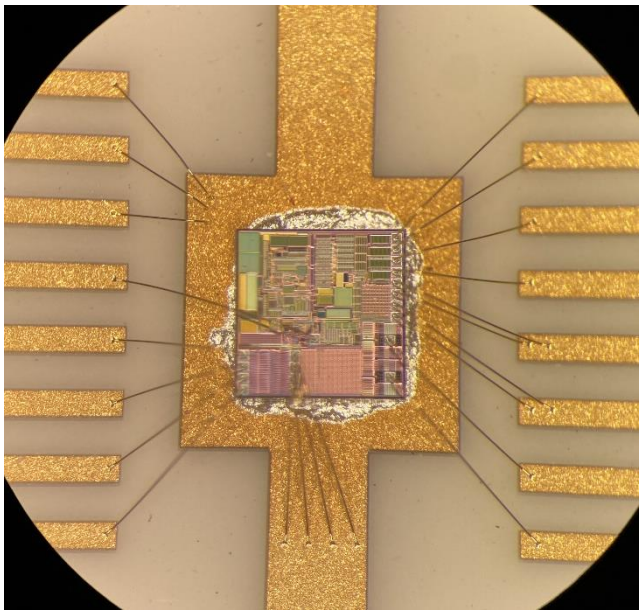

Figure 6: CHT-RIGEL in a die format epoxied to the gold pad on the ceramic PCB.

Wire bonding is accomplished in steps: (1) the die is epoxied to the metal plating in the center of the PCB with Duralco 124, which has a max operating temperature of 340 ˚C, (2) the epoxy is cured, (3) a 0.001" wire is ball-bonded between the die and PCB to make the electrical connection. When we were creating our first sample, the epoxy debonded from the metal plating during the wire bonding stage. The bonding may have failed because the gold was not completely clean.

Alternatively, there may have been a CTE mismatch between the epoxy and metal plating: according to the Duralco 124 datasheet, the epoxy has a CTE of ~40 ppm/°C, but lab tests showed a CTE of ~200 ppm/°C. Our second sample survived the wire bonding process (Figure 6), but electrical testing revealed only partial performance; the voltage would come on and off, even at room temperature. Occasionally, the device would stabilize with a 5V output (as defined in the circuit), so we further evaluated the PCB bonding in the oven. The device was brought to a temperature of 250 °C and functioned continually for an hour at that temperature. However, when the temperature was increased to 300 °C, the bonded PCB stopped functioning and did not resume function after cooling. Observation shows the wire bonds were still intact, but damage was observed on the chip. Future step will be to replace the Duralco 124 with sintered silver and repeat the tests with a new IC.

D. Conformal Coating

Hypothesizing that a conformal coating over the electrical connections could beneficially strengthen the mechanical bond between the IC and PCB. Multiple companies' off-the-shelf HT epoxies were evaluated.

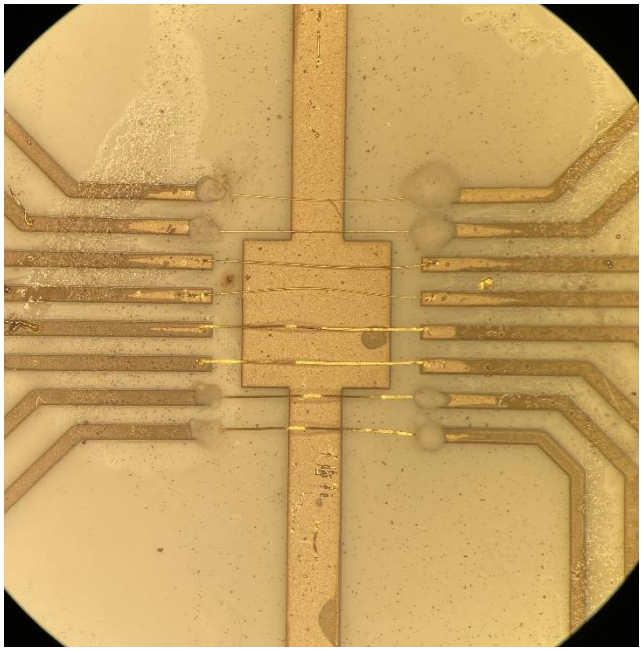

Figure 7: Eight wire bonds were applied to the ceramic PCB with small amount of epoxy applied to the region of the wire bond attached to the metal traces. Top four wires in the figure are 1-mil gold wires that were ball bonded. Bottom four wires are 0.5x2-mil gold wires that were wedge bonded.

A desirable epoxy for this application would have (1) a low viscosity (to allow application of a thin layer over the structures), (2) HT operation, and (3) a CTE similar to that of the ceramic PCB (6–9 ppm/˚C). Eventually Micro Measurements selection of 800 ˚C epoxies: WC-16 (CTE 7.2 ppm/˚C), HG-1 (10.8 ppm/˚C), and NCC-3 (12.6 ppm/˚C) were down selected for the application. Due to the close CTE match, we expected WC-16 to be the most promising candidate; however, for thorough analysis, we tested all three epoxies on HT resistors that were gold-tin soldered to a ceramic PCB. For three weeks at 300 °C, all three epoxies supported the resistors with no observable degradation. To further evaluate the epoxy, gold-wires were wire bonded onto the ceramic PCB creating electrical jumpers across a set of traces. Four 1-mil wire bonds were ball bonded and another four 0.5x2-mil wire bonds were wedge bonded. To assess the impact of the conformal coating, only two wedge bonded wires and two ball bond wires were coated with the WC-16 epoxy (Figure 7). After 48 hours in the oven at 300 °C, no debonding was observed and resistance was maintained across each of the eight wire bonds. Further oven testing will be conducted on the sample.

III. Conclusion

Sandia's preliminary experiments indicate that ceramic PCBs, gold-tin soldering, wire bonding, and HT conformal coating all show promise for significantly improving the operation of EESs exposed to high temperatures (≥ 300 °C) for extended periods. However, further testing will be required to identify yield and confirm performance under vibration. One major concern is that the gold-tin is reaching a liquidous state at 300 °C, but the conformal coating may compensate by acting as a mechanical support. These techniques will advance the development of HT electronics, for long-duration geothermal hardware.

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