FINITE ELEMENT ANALYSIS ON WIRE BOND BREAK DURING TC AND PTC: EVALUATING ENCAPSULANT MATERIAL CHANGE AS A POTENTIAL SOLUTION

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ABSTRACT

Finite Element Analysis (FEA) proves invaluable for semiconductor package failure analysis and assessing proposed solutions for various assembly-related challenges. This study focuses on investigating wire breakage during thermal cycling (TC) and power and temperature cycling (PTC) through FEA. Results indicate that the use of soft silicone as an encapsulant material can lead to catastrophic failure during TC/PTC due to maximum stress concentration in the wire's neck region, consistent with failure analysis reports pinpointing the neck as the primary site of wire breakage. Furthermore, substituting soft silicone with hard epoxy significantly reduces deformation of the 1.0mil Au wire by approximately 2-3 times lower than that of soft silicone, as evidenced by FEA. However, experimental results reveal broken wires in units with hard epoxy encapsulant at approximately 800 cycles, highlighting that a simple material change does not guarantee wire survival during TC and PTC. Thus, further investigation is necessary to identify additional factors contributing to wire breakage observed in automotive device during TC and PTC.

1. 0 INTRODUCTION

High-power semiconductor lasers have been widely used in medical, aerospace, military fields, automotive, to name a few, due to their small size, lightweight, high electro-optical conversion efficiency, and easy monolithic integration [1]. In general, laser with levels above 100 mW for narrow-stripe, single-mode devices, and levels above 1 W for all single- and multi-emitter lasers are considered high power [1]. Wire bond is a critical interconnection between substrates and chips, which basically transmits power and signal as well as aid heat dissipation of the device during operation [2]. Wire bond failure predominantly occurs due to thermo-mechanical fatigue induced by (i) shear stress generated between bond pad and wire, (ii) repeated flexure of wire, and (iii) shear stress generated between bond pad and substrate [3]. Typically, these stresses arise due to coefficient of thermal expansion (CTE) mismatch between wires and substrate materials. Residual stresses may arise as a result of the wire bonding process [3]. The prevailing failure mechanism is highly dependent on the operating environment, wire and bond pad material, and wire geometry [3].

Another critical component of a semiconductor package is the encapsulation, which serves as protection of the chips and wires from harsh environmental conditions, such as moisture and dust [2]. Silicone is one of the widely used encapsulant materials in electronic applications due to its several advantages such as controlled refractive index, tunable hardness, high optical transparency in the UV-visible region, and excellent thermal stability against yellowing [4]. Furthermore, due to the silicone's relatively low Young's modulus, it is expected to exert minimum stress to the electronic components [5]. However, one of the challenges in using silicone material is the high likelihood of water vapor diffusion owing to its high permeability which could accumulate at delaminated surfaces, resulting to corrosion of the components and circuits [5]. Another challenge is delamination which can be induced by the high thermal stress and poor interfacial adhesion strength between the encapsulation and components [5].

In this study, wire break was observed on the 1.0 mil Au wire of automotive device during thermal cycling (TC) and power and temperature cycling (PTC). The encapsulant material used for the affected device is a soft silicone. Pulse width and optical power drop ranging between 10-24% were observed on units post TC1000. Internal failure analysis was conducted to examine the defect signature of the wire break on neck. Fig. 1 shows the post decapsulation photos of the units that failed in TC1000. As for PTC, no optical power was observed on units as early as 500 cycles. Similar to TC, wire break on neck was also observed after decapsulation. An earlier study has cited the occurrence of wire creep failure mechanism in gold wires, characterized by break along slip planes or a fracture at grain boundaries [6]. This type of failure is often encountered during thermal cycling reliability tests [6]. Other studies have also cited that the prominent deformation mechanism of gold when subjected to relatively high temperature is through dislocation motion, slip planes, grain boundary sliding, and diffusion creep [7-8].

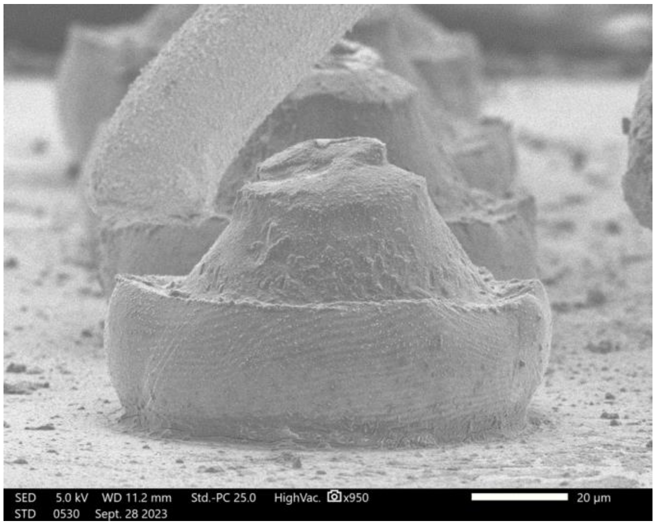

Fig. 1. SEM image on the wire break on neck observed after TC1000.

Finite element analysis (FEA) is a useful tool in analyzing potential failure position in power modulus. Its multiphysics features allows accurate emulation of the electro-thermo-mechanical domains of a power module packaging [9]. However, one of the challenges in FEA simulations is the difficulty to take into account the evolution of geometry which is typically correlated to the crack phenomena [9].

In this study, FEA was utilized to investigate the thermo-mechanical stress experienced by the wire and correlate it with the wire bond failure observed at TC and PTC. Moreover, FEA was also used to study the deformation and thermo-mechanical stress experienced by the 1.0 mil Au wire using hard epoxy as encapsulant material.

2. 0 REVIEW OF RELATED WORK

Not applicable

3.0 METHODOLOGY

3.1 Materials

In this study, automotive device used for sensor application were utilized. The units were processed as normal at die attach. The gold wire used is 1.0 mil 99.99% Au. The units were processed as normal during assembly at Excelitas Manila. Units were subjected to PTC and TC at Excelitas Montreal, in accordance with AEC-Q conditions.

3.2 Finite Element Analysis (FEA) using ANSYS

In this study, FEA was conducted using ANSYS software. The principle of multi-level modeling was utilized in this study similar with Fiori and Orain's methodology [10]. The following steps are followed:

- Compute first a simulation at a global level to get displacements field
- Locate the maximum strained area, i.e. the future location of the micro model
- Apply the displacement field calculated at the macro level as boundary conditions of the micro model in order to reach the local stress field

Fig. 2 shows the typical process flow for the multi-level and homogenization technique used in FEA. In FEA, it is critical to describe the materials and the layout in the macro/global model to accurately calculate the displacement fields. This requires homogenization process which considers the geometrical details by modifying the mechanical properties without meshing all the bond pad layers. Moreover, a half symmetry was used. Other assumptions used in the FEA are as follows:

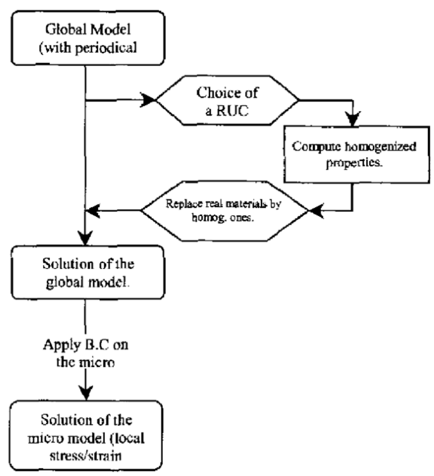

Figure 2. Process flow chart for multi-level and homogenization technique.

The material properties used in the FEA are summarized in Table 1.

Table 1. CTE and elastic modulus of the various material

Material	CTE (ppm/°C)	Elastic Modulus (MPa)	Transition temperature[1] (°C)
Au wire	14.2	85,000	1063
Soft silicone	220	1	-120
Hard epoxy	CTE_1: 60 CTE_2: 210	3,000	130
LCP	13.5	15,000	80-120
Glass	7.2	72,900	557
GaAs	5.73	84,800	NA
Die Attach Epoxy	350	12,000	≥80
FR4	15	24,000	>150

[1]*For metals, values reflected are melting point (T_m) while for polymers, values represent the glass transition temperature (T_g). For glass, the value corresponds to the transformation temperature.*

In the absence of experimental data, the yield stress of the 1.0 mil Au wire was estimated based on the hardness values indicated on the technical data sheet. The yield strength (YS) was estimated using the general empirical relationship of Vicker's hardness (HV) to yield strength, which is HV ~ 3YS. Table 2 summarizes the yield strength for the ball, heat affected zone (HAZ), and after HAZ.

Table 2. CTE and elastic modulus of the various material

Location	Yield Strength (MPa)
Ball	192.87
HAZ	192.87
After HAZ	228.83

3.3. Experimental AEC-Q TC runs

The automotive device was subjected to thermal cycling (TC) conditions in accordance with AEC-Q requirements. The objective of this experiment is to correlate the FEA results to the actual failure experienced by the units during TC conditions. Units with hard epoxy and soft silicone as encapsulant material were ran simultaneously in TC. Below Table 3 shows the visual inspection points were identified to assess the relative wire deformation of the 1.0 mil Au wire as the TC progressed from 0 to 1000 cycles. This experiment was conducted at Excelitas Manila Reliability Laboratory and followed the AEC-Q requirements for TC.

Table 3. Visual inspection points during TC

Point	No. of cycles
1	100
2	300
3	500
4	800
5	1000

4.0 RESULTS AND DISCUSSION

For the FEA, a global model was used first to determine the regions in the device with maximum displacement. Fig. 3 shows a 3D drawing of the area of interest. It shows the various materials as well as their corresponding boundaries/interfaces. In this study, a half-symmetry was used owing to the inherent symmetry of the device. Moreover, the other half is basically identical and follows all the assumptions and calculations that were applied to the reduced model under analysis. A conformal mesh was employed in this FEA, assuming common nodes between bodies. This streamlined approach eliminated the need for contact conditions, enhancing efficiency and accuracy. Furthermore, this methodology notably decreased the overall run time of the FEA.

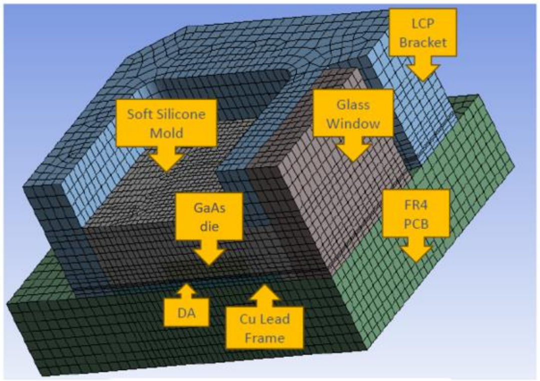

Figure 3. 3D drawing of area of interest showing the different material interface

Fig. 4 shows displacement results on the global model for both soft silicone and hard epoxy encapsulation wherein the effect of the much lower CTE of the hard epoxy epoxy showed a reduction of almost an order in magnitude in the deformation, as compared to the soft silicone. Even with a much higher modulus for the hard epoxy, the expected deformation experienced by the 1.0 mil Au wire is still approximately 2-3 times lower.

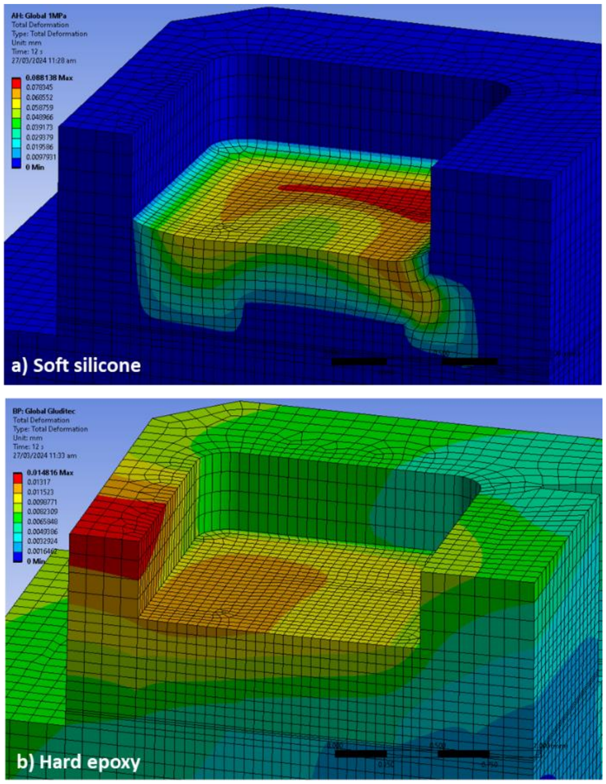

Figure 4. Global deformation plots of a) soft silicone and b) hard epoxy

FEA results showed that using a soft silicone as encapsulant material could lead to catastrophic failure during TC/PTC. This is attributed to the maximum stress experience on the neck region of the wire. This observation aligns with failure analysis reports that specifically identify the neck as the location of wire breakage. This is also further supported by the much lower yield strength exhibited by the neck, which is part of the HAZ, compared to the bulk wire (after HAZ) and ball region. Hence, there arises a necessity to investigate alternative encapsulant materials capable of enduring 1000 cycles of TC and PTC.

A hard epoxy was further studied using FEA as a potential alternative encapsulant. Compared to the soft silicone, the hard epoxy exhibits a much higher Young's modulus and thus, much harder. Fig. 5 shows the local deformation plots comparison of the 1.0 mil Au wire with soft silicone and hard epoxy as encapsulant material. Due to the much lower CTE of the hard epoxy, a reduction in the global deformation plot to almost an order in magnitude was observed. Furthermore, the local model shows that even with the increased modulus of the hard epoxy, the overall wire deformation is still approximately 2-3 times lower than that experienced with the soft silicone.

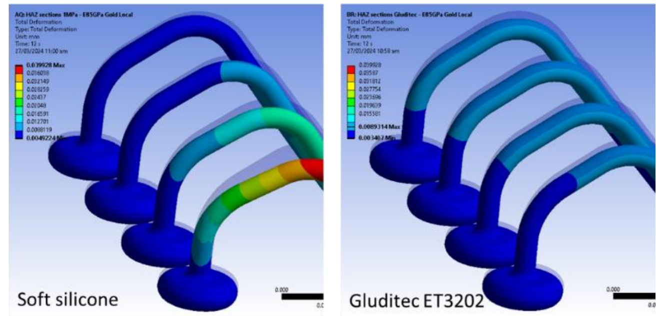

Figure 5. Deformation plot comparison on soft silicone and hard epoxy

The accumulated plastic strain (see Fig. 6) for the soft silicone shows that plastic strain is expected to develop and progress over repeated temperature cycling which indicates that the 1.0 mil Au wire will eventually succumb to low cycle fatigue (N<10,000 cycles). Low cycle fatigue regime is typically characterized by inelastic strain rather than stress, which is the case for high cycle fatigue. When an alternative encapsulant such as a hard epoxy was used, it was observed that the accumulated plastic strain was reduced by around 50%. The lower CTE resulted to a net positive on the wire bond performance during temperature cycling. In order to ensure the 1.0 mil Au wire survives the low cycle fatigue regime, it is imperative to have a delta per cycle that is nil. The hard epoxy encapsulant showed a lower delta per cycle that that of the soft silicone.

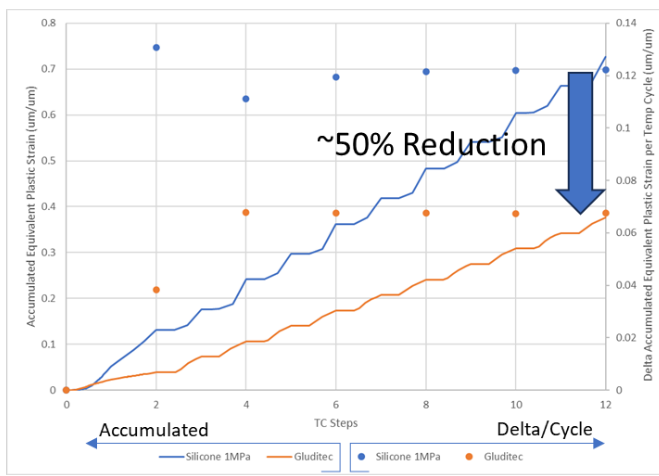

Figure 6. Accumulated plastic strain and delta per cycle of soft silicone and hard epoxy

In order to correlate the findings from the FEA study, automotive units that have undergone TC as per AEC-Q requirements were investigated. Two experimental legs: (i) soft silicone and (ii) hard epoxy as encapsulant material were subjected to TC. Five units per experimental leg were used. Fig. 6 shows the comparison of time zero and TC100 wherein for the soft silicone leg, broken wires were already observed on 610462 and 90303. Moreover, surface roughening on the neck region of Au wire was already evident at 100 cycles.

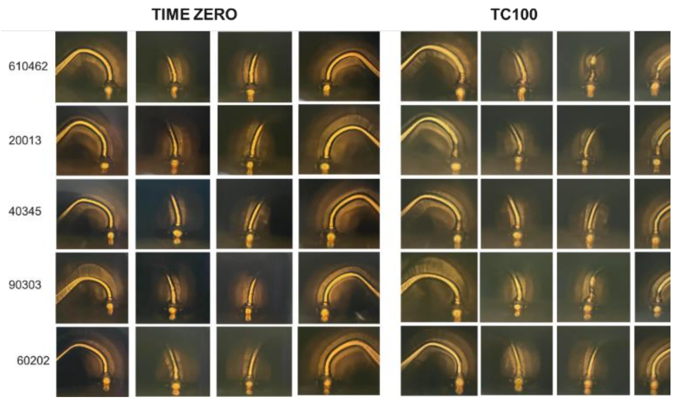

Figure 6. Time zero and TC100 comparison on automotive units processed with soft silicone encapsulant

As the number of cycles progressed up to 1000 cycles, it is worth noting that surface roughening observed on the neck region became worse which suggests that the neck region of the wire experiences the highest stress during TC. This observation is consistent with the deformation plots obtained earlier from FEA. Furthermore, Fig. 7 shows that the wires exhibited a "kneeling" phenomenon which could be a combined effect of the soft silicone and the confinement brought upon by the LCP bracket, or some other aggravating factor in the device configuration.

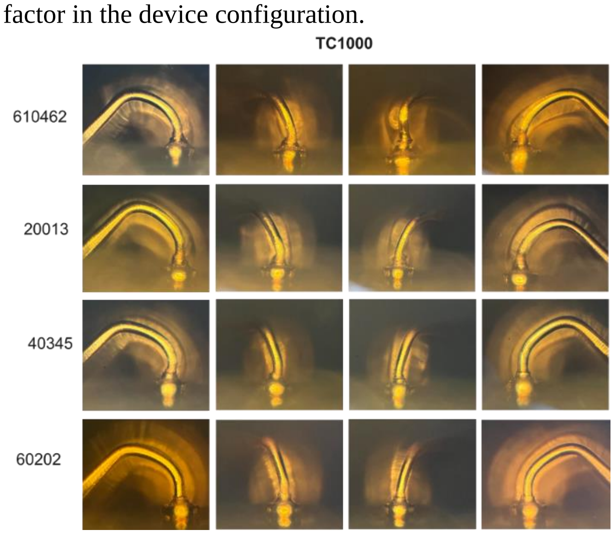

Figure 7. TC1000 visual inspection on units with soft silicone encapsulant (*Note: Unit 90303 was subjected to decapsulation at TC800*).

On the other hand, for the automotive units with hard epoxy encapsulant, Fig. 8 shows the time zero and TC100 comparison. Results showed that there was no evident surface roughening and movement on the Au wires. Furthermore, no broken wires were observed at 100 cycles.

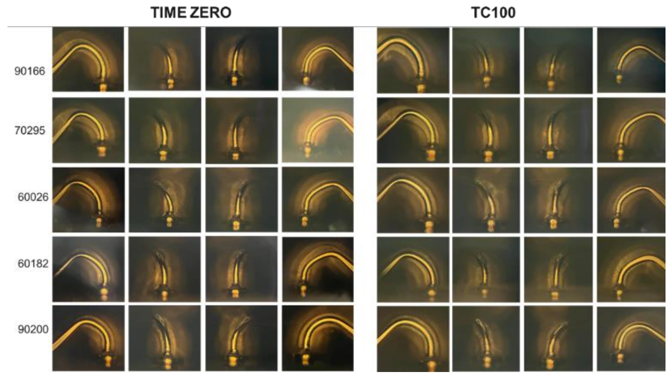

Figure 8. Time zero and TC100 comparison on automotive units processed with hard epoxy encapsulant

However, at around 800 cycles, the units with hard epoxy encapsulation exhibited evident necking which usually precedes wire break on neck of the Au wire (see Fig. 9). Comparing with soft silicone encapsulation, hard epoxy units showed minimal to no surface roughening in the neck region, when compared to the time zero condition. This further supports the FEA findings wherein the deformation experienced by the Au wire in hard epoxy is up to 2-3 times lower than that induced by the soft silicone.

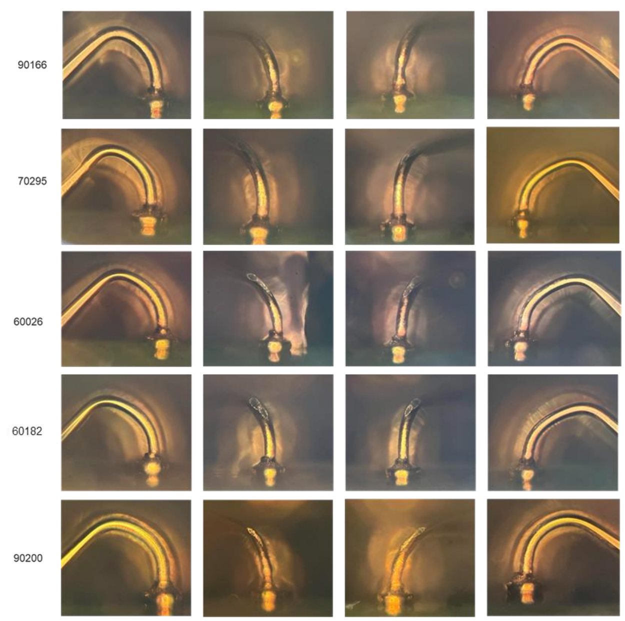

Figure 9. TC800 visual inspection on automotive units with hard epoxy encapsulant

Further x-ray inspection of the hard epoxy units at 800 cycles revealed the presence of broken wires, as illustrated in Fig. 10. These broken wires were not evident initially at time zero nor at 100 cycles. Despite the FEA study indicating reduced deformation with the use of a hard epoxy like hard epoxy for encapsulation, this alone does not ensure wire survival for at least 1000 cycles, a crucial requirement within the low cycle fatigue regime and for AEC-Q standards. Merely transitioning the encapsulant material from a soft silicone to hard epoxy, as observed in the case of this automotive device, does not guarantee passing the TC and PTC requirements. Additional factors warrant investigation in subsequent studies.

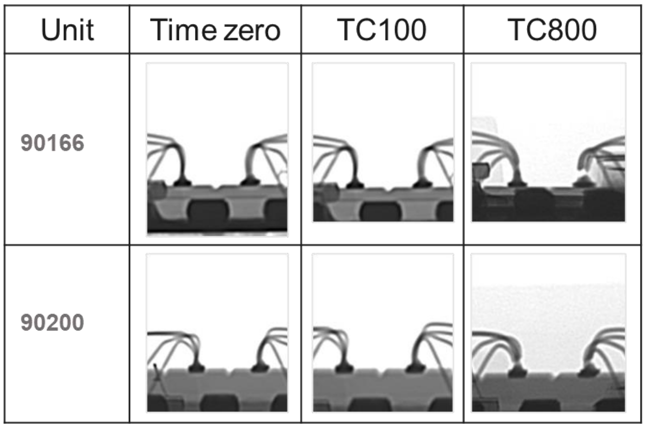

Figure 10. X-ray inspection of hard epoxy at time zero, 100 cycles, and 800 cycles

5.0 CONCLUSION

This study utilized FEA to investigate wire breakage observed during the thermal cycling and power thermal cycling of automotive units encapsulated with soft silicone. FEA results indicated that substituting soft silicone with a hard epoxy as the encapsulation material could reduce deformation of the 1.0 mil Au wire by 2-3 times. However, experimental observations revealed broken wires in hard epoxy units at approximately 800 cycles. These findings highlight that transitioning from a soft silicone to hard epoxy does not guarantee wire survival for the required 1000 cycles, a crucial requirement for AEC-Q standards. Further investigation is warranted to identify additional stress factors influencing the performance of Au wires in this automotive device.

6.0 RECOMMENDATIONS

This study establishes a precedent that simply altering the encapsulant material of the affected device does not ensure the passage of 1000 cycles of TC and PTC, which is a critical AEC-Q requirement. The authors recommend further investigation into other materials within the device that may exacerbate the stress experienced by the 1.0 mil Au wire during TC and PTC. Additionally, it is crucial to review the overall device design, particularly critical geometries that may also serve as stress concentrators. These aspects warrant further exploration to pinpoint the root cause of wire breakage during TC and PTC.

7.0 ACKNOWLEDGMENT

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9.0 ABOUT THE AUTHORS

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10.0 APPENDIX

Not applicable.

Other Pointers:

One should refrain from beginning a sentence with numbers or acronyms.

The first time an acronym is used in the text, it should be defined. When the paper has lots of acronyms in use, a list of definitions in a separate section can be created.

Text should be written in third person passive mood. Refrain from the use of personal pronouns.

Check to see if your figures have labels which are readable. The figure should be able to convey the message without one's having to read the text of the manuscript. Hence, the figure captions should be able to explain the figure.

Do not be redundant with your data presentation, some people have the tendency to show the tabular data form as well as the chart. Whenever possible, charts and graphs are preferred over tabulations of data points.

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